Astronautics Corporation of America
Technology Center
5800 Cottage Grove Road
Madison, WI 53716
(608)221-9001

April 1988
March 1992 (Revised)

Technical Summary

A Review of Findings of a Study of Rocket Based Combined Cycle Engines Applied to Extensively Axisymmetric Single Stage to Orbit Vehicles

Prepared by:

Richard W. Foster

BACKGROUND

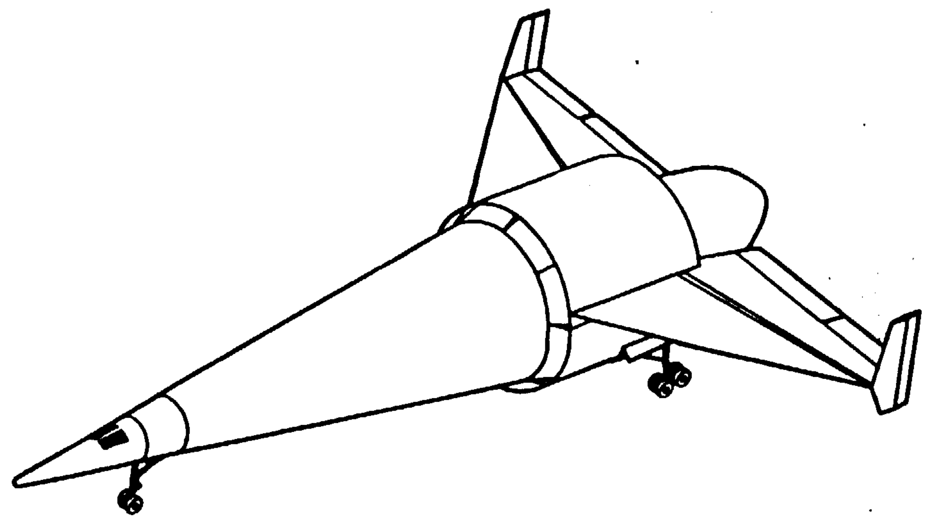
This technical summary was prepared in early 1988. It is based on the findings of a study carried out for the USAF Astronautics Laboratory by Astronautics Corporation of America and the Martin Marietta Aerospace Group (MMAG). The findings of this study are reported in:

Foster, R.W., Escher, W.J.D., and Robinson, J.W., Air Augmented Rocket Propulsion Concepts, Final Report, USAF Astronautics Laboratory Report AFAL-TR-88-004, April 1988

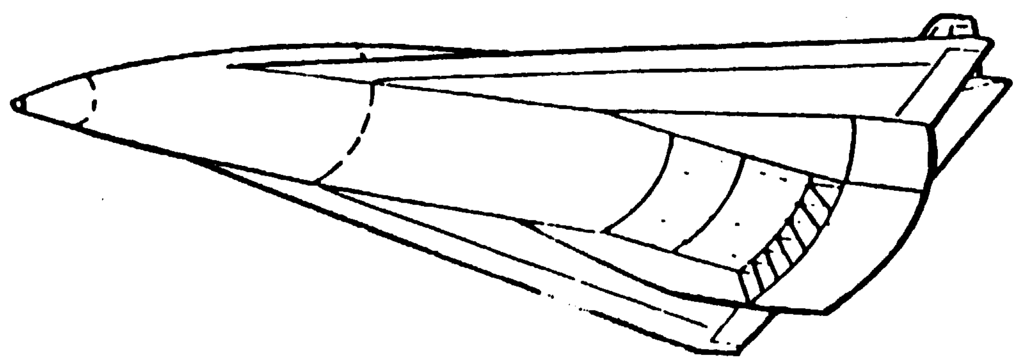
PLACING THE VEHICLE STUDIED IN CONTEXT WITH OTHER ALTERNATIVE

Two figures are presented on the following page. The first figure defines, by illustration, what we mean by "Extensively "Axisymmetric" and "Non-Axysymmetric" vehicle configurations. The second figure places Rocket Based Combined Cycle (RBCC) propelled "Extensively "Axisymmetric" vehicles in context with all-rocket and other airbreathing orbital vehicles.

Placing the Study Vehicle in Context

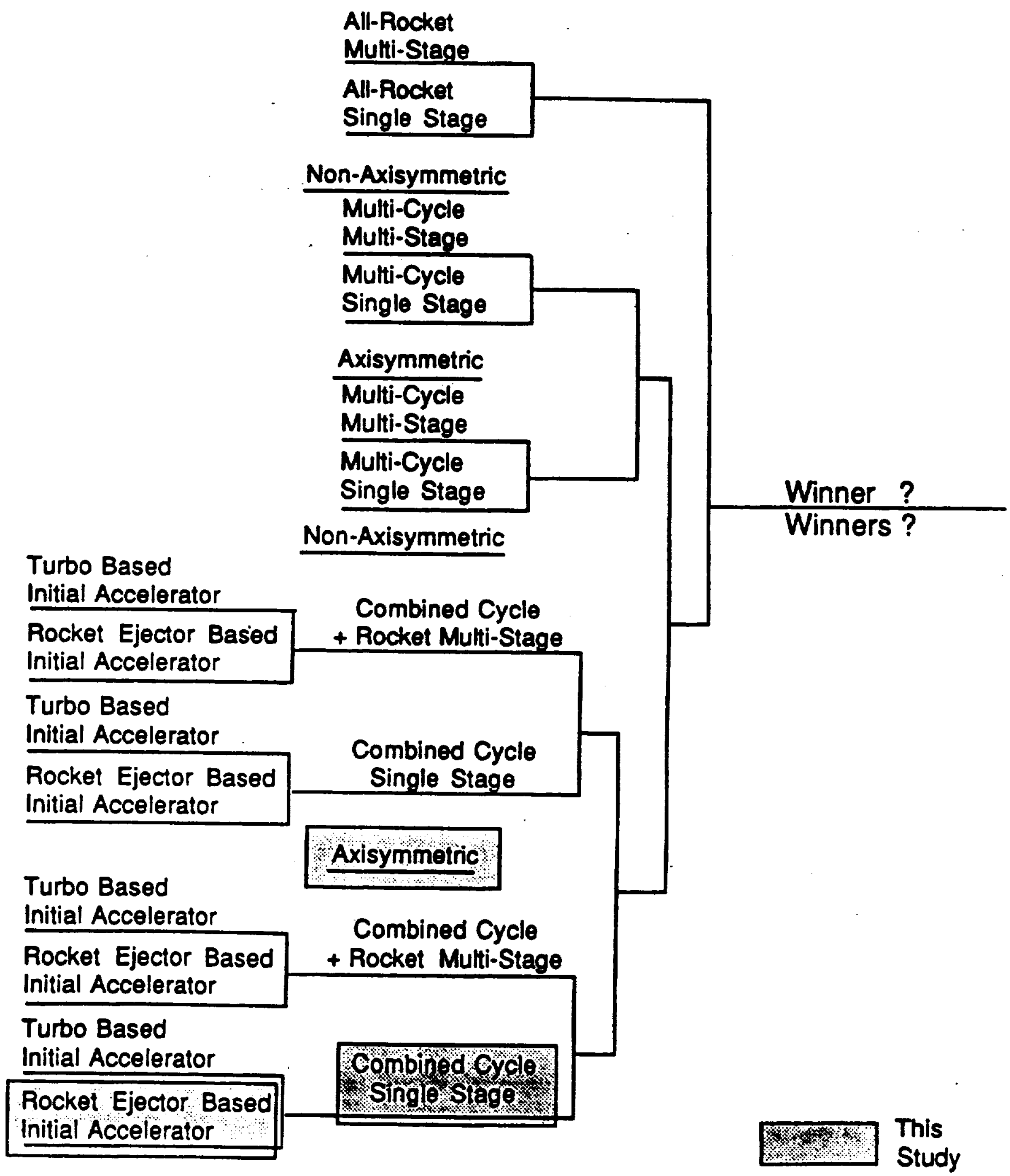


Form: Extensively Axisymmetric



Form: Non-Axisymmetric

Placing the Study Vehicle in Context



PAYLOAD COMPARISONS

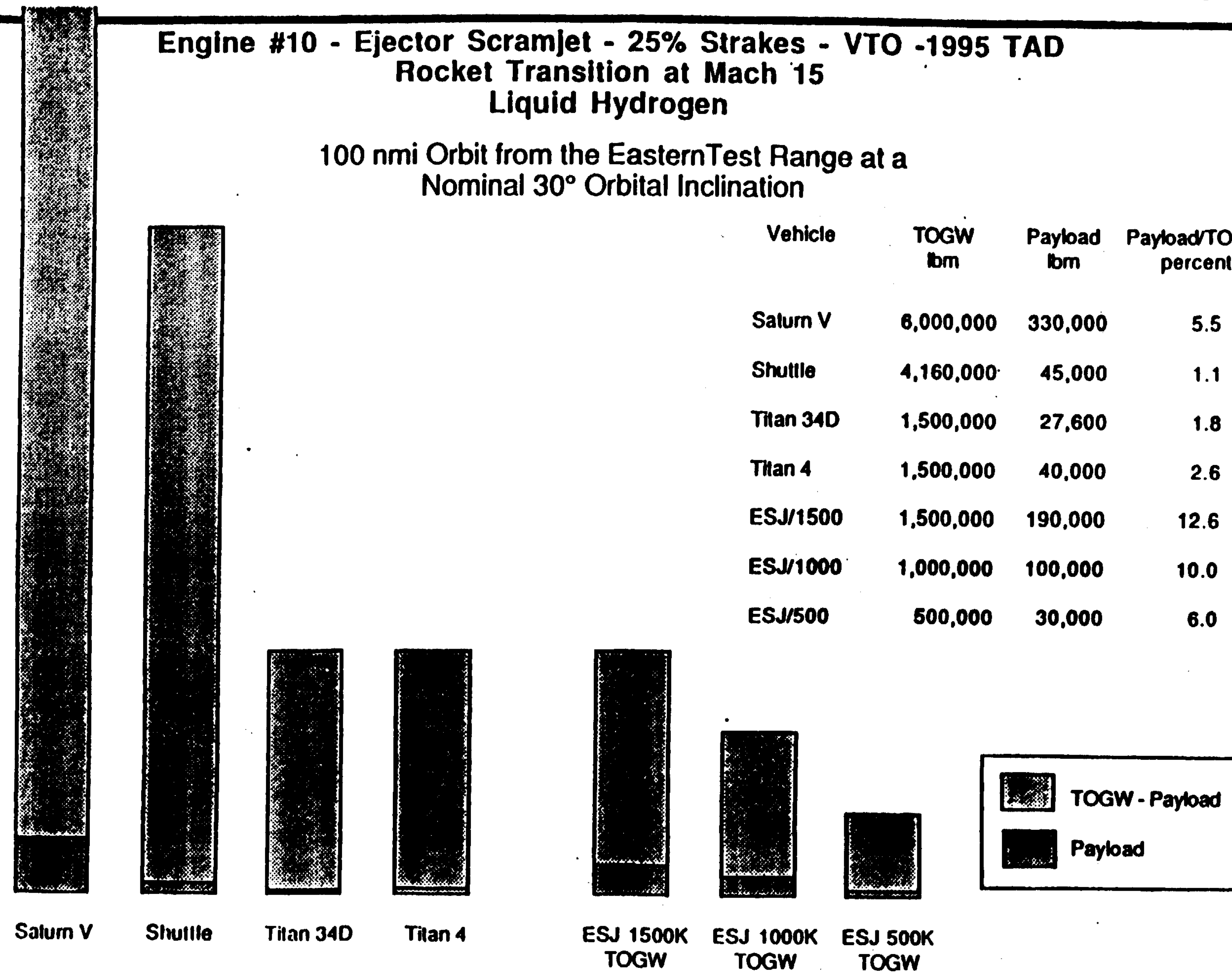
The estimated payload delivery capability of the RBCC/SSTO VTOHL vehicle systems studied is shown in comparison to all-rocket multi-stage alternatives in the facing figure.

Multistage All-Rocket & Extensively Axisymmetric RBCC SSTO GLOW's & Payloads

Engine #10 - Ejector Scramjet - 25% Strakes - VTO -1995 TAD
Rocket Transition at Mach 15
Liquid Hydrogen

100 nmi Orbit from the EasternTest Range at a Nominal 30° Orbital Inclination

Vehicle	TOGW lbm	Payload lbm	Payload/TOGW percent
Saturn V	6,000,000	330,000	5.5
Shuttle	4,160,000	45,000	1.1
Titan 34D	1,500,000	27,600	1.8
Titan 4	1,500,000	40,000	2.6
ESJ/1500	1,500,000	190,000	12.6
ESJ/1000	1,000,000	100,000	10.0
ESJ/500	500,000	30,000	6.0

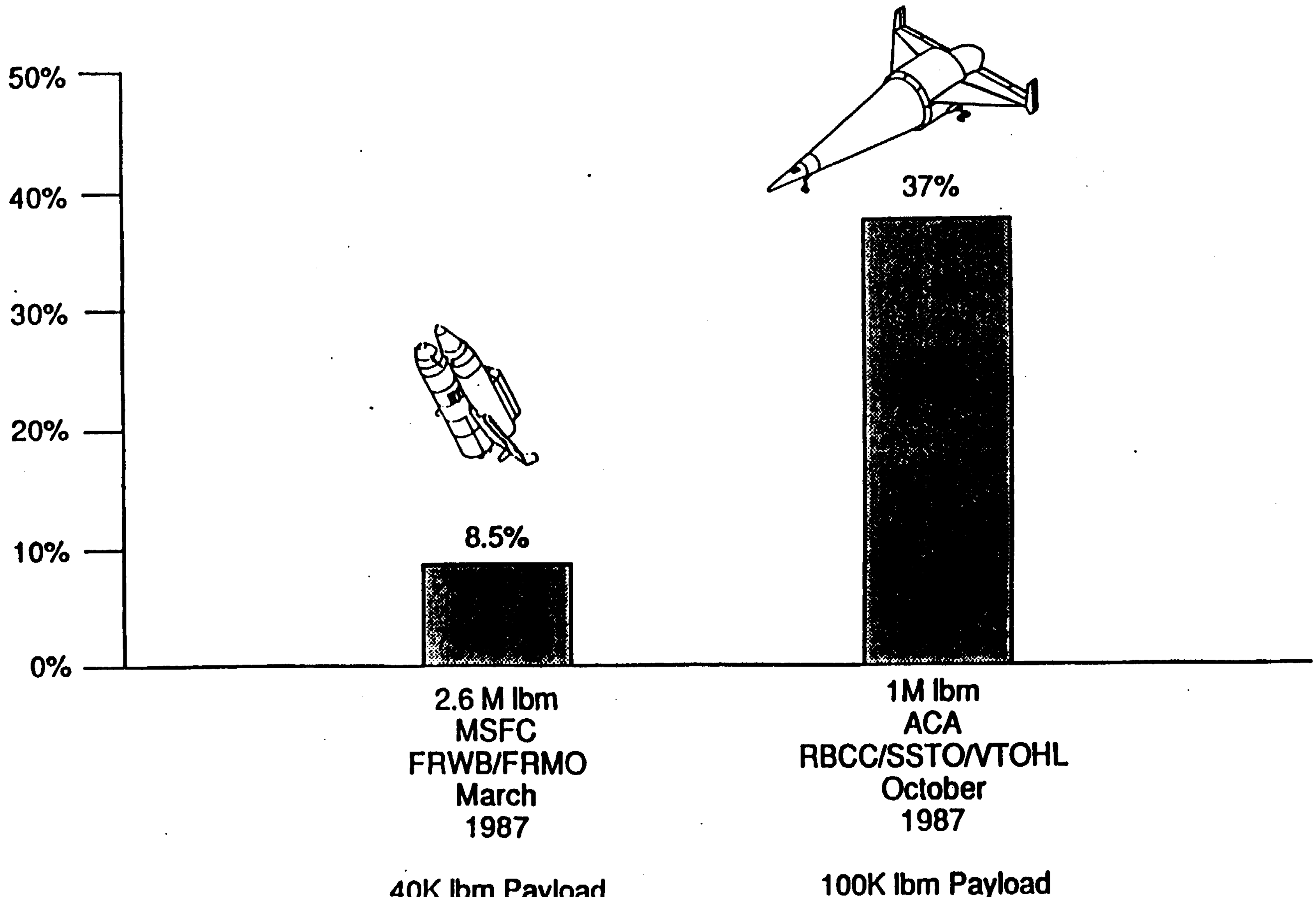


PAYLOAD AS A PERCENT OF DRY WEIGHT - A SYSTEM HARDWARE COST INDICATOR

In terms of payload as a percent of dry weight, the RBCC/SSTO/VTOHL design approach outperforms the current all-rocket two-stage systems typified by the MSFC March 1987 study findings for the Fully Reuseable Winged Booster (FRWB) and Fully Reuseable Manned Orbiter (FRMO) two-stage combination.

This payload/inert weight ratio is due to high effective specific impulse of airbreathing engines, in the range from 650 to 700 seconds, combined with a "rocket-like" extensively axisymmetric structural design, which yields propellant mass fractions comparable to those achieved in rocket based systems.

Recent Study Findings - Payload/Dry Weight for RBCC SSTO and Fully Recoverable Winged Booster/Fully Recoverable Manned Orbiter



LIFE CYCLE COST (LCC) ESTIMATIONS - GROUNDRULES

A life cycle cost estimation for an RBCC/SSTO/VTOHL vehicle system was developed by Martin Marietta Denver Aerospace (MMDA) using MMDA's STAS cost model. This chart presents the assumptions under which that LCC analysis was carried out.

LIFE CYCLE COST (LCC) ESTIMATION

LCC Groundrules and Assumptions

- Fiscal Year 1987 Dollars
- Point Design Vehicle - 440 klb TOGW
- Structures and Engines Life = 100 flights
- Engines: Recycled Supercharged ScramLACE (#32)

- Stage-Up reliability = 0.996
- Stage-Down reliability = 0.996
- Mission Success = 0.992

- IOC = 2005
- 1997 - 2002 DDT&E

- 5 test vehicle in DDT&E phase

- 2 main operating bases (WTR & ETR)

- Cost of LH_2 = \$2.00/lb
- Cost of LOX = \$0.05/lb
- Cost of SLH_2 = \$4.00/lb

- Normal turnaround time for ground operations processing = 5 days (1 shift/day)

- Launch site facilities: Vehicle Service Facility
  Operations Control Center
  Propellant Servicing Area

- Payload encapsulation performed off-line (i.e., not in the vehicle-turnaround timeline).

- No pad or landing strip built (assume use of existing runways or pads).

- STAS Mission Model Civil Option II/DOD Option 2

- Vehicle capability 40klb LEO @ 28.5° - 100% manifest load factor.

- DDT & E Engines = \$2B , 1st Unit Cost = \$81M

- Payload lost cost is a function of flight rate, payload capability, reliability, and payload \$/lb.

MARTIN MARIETTA

OPERATIONS AND SUPPORT COSTS ESTIMATION - SSTO Operations

The findings of the AFAL study indicate an Operations and Support cost of $160/Lb of payload delivered to the 100 nmi orbit.

LIFE CYCLE COST (LCC) COMPARISON
BASELINE - OPERATIONS AND SUPPORT COSTS

Operations $ / LB Payload Comparison: 28.5° Inclined 100 n.mi

VEHICLE	O & S BASED SPECIFIC COST
SPACE SHUTTLE	$2646 / LB - PAYLOAD
POINT DESIGN (THIS STUDY): 440 lbm TOGW 10,000 lbm Payload	$160 / LB - PAYLOAD

0717

CAPABILITY - UTILITY

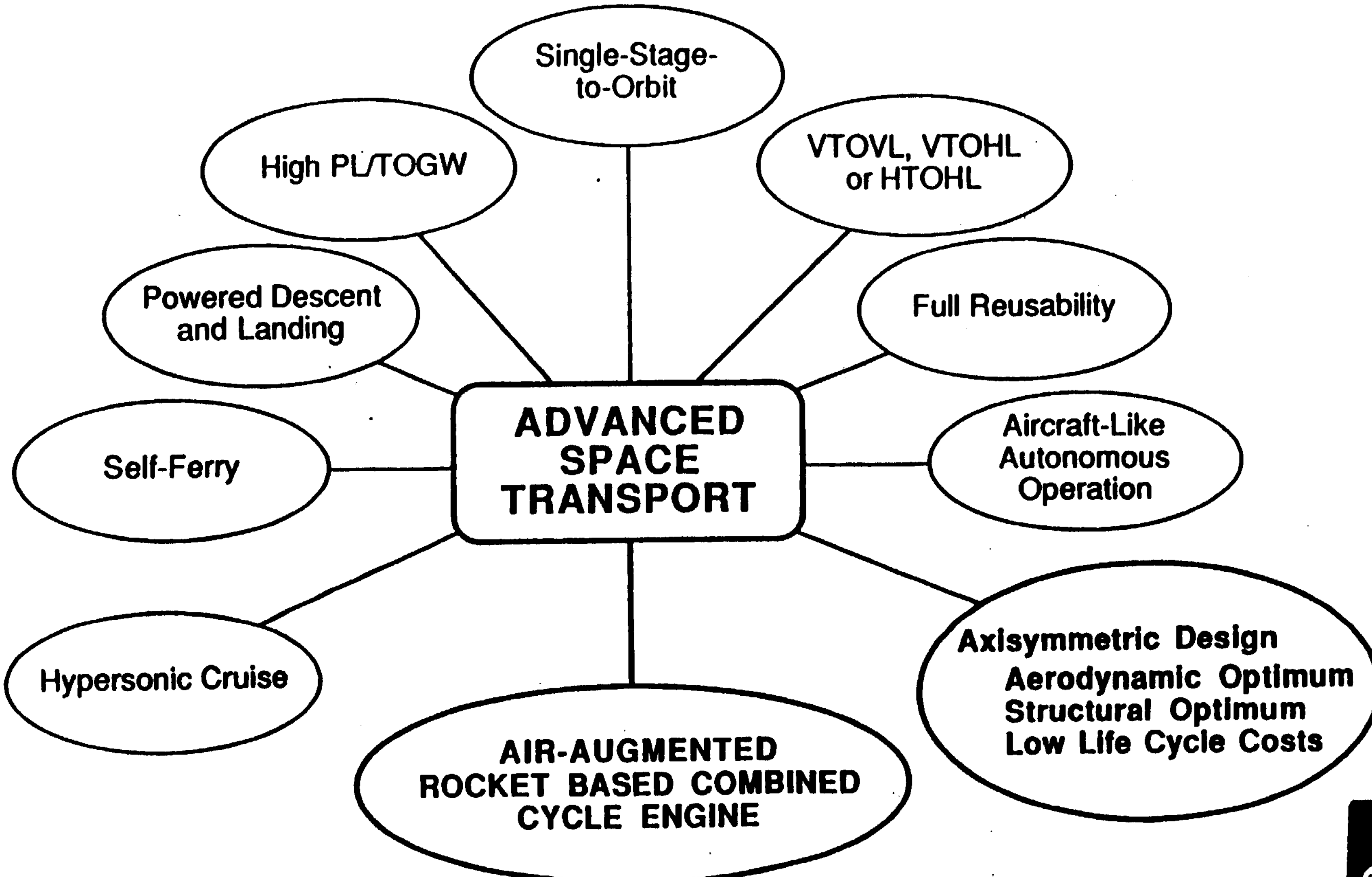
The previously described superiority of the RBCC/SSTO/VTOHL design approach in terms of both payload fraction and payload to dry weight is available in a system with many additional characteristics and capabilities that yield a vehicle configuration that should have a high utility value - it should be useful in a diversity of missions in addition to the SSTO mission.

The range of atmospheric missions that could be performed by a vehicle of this design should be explored.

The range of low earth orbit and higher orbit missions with and without full or partial orbital refueling should be investigated.

No quantitative comparison of the advantages of extensively axisymmetric design over non-axisymmetric design in terms of aerodynamic design superiority, structural design superiority or lower life cycle costs has been carried out to date. This must be done before the advantages and disadvantages of the two alternatives can be compared in any meaningful way. Somehow these comparisons must be brought to some form of common baseline.

CAPABILITY - UTILITY



1030

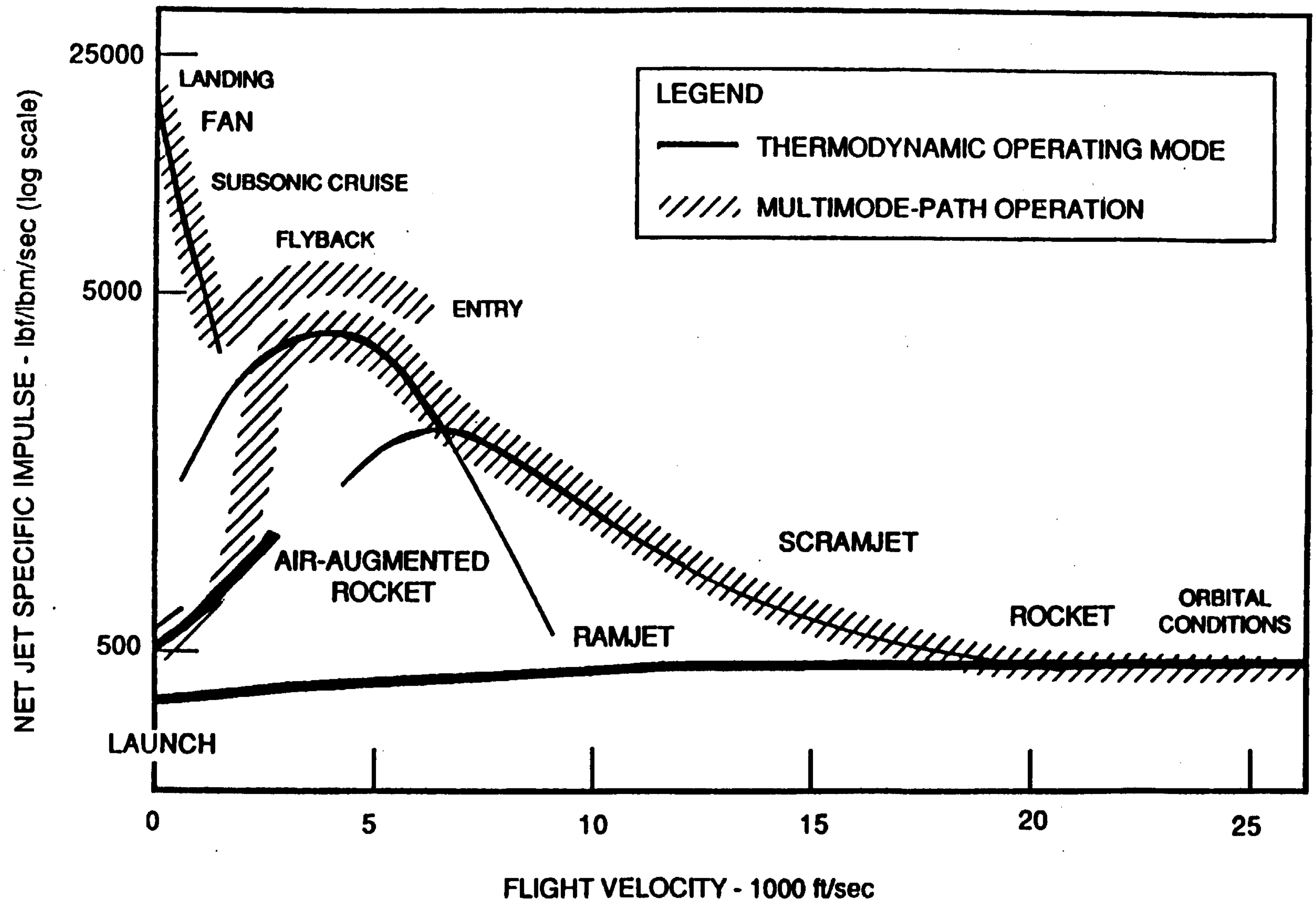
MULTIMODE PERFORMANCE OVER THE MISSION PROFILE

The RBCC design approach provides an integrated engine that is capable of starting from zero forward velocity using an air augmented rocket system, transitioning to ramjet, transitioning the scramjet and finally transitioning to rocket mode operating to Mach 25 in a single flow passage.

One variation of the RBCC propulsion system design incorporates a fan subsystem that serves to supercharge the air augmented rocket and ramjet modes. More importantly, the fan subsystem provides very high Isp values which enable multiple "go-around" capability and a significant atmospheric cruise capability. The Fan subsystem, with plenum burning, can provide vertical landing capability. The value of this capability in relation to the weight penalty must be determined by the user.

MULTIMODE PERFORMANCE OVER THE MISSION PROFILE

EXAMPLE: SUPERCHARGED EJECTOR SCRAMJET (ENGINE #12)



0341

SELECTED ENGINE TYPE

There are over 31 variations of design approach to RBCC engine systems - it is a "family" of engines. The original investigations of these variations was carried out in the 1960's.

Five variants of the "family" met the requirements for SSTO propulsion. These were:

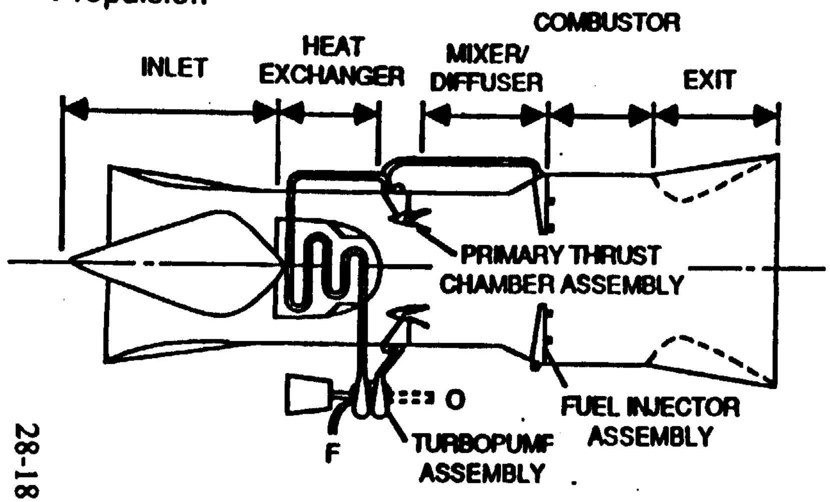
- Engine #10 - Ejector Scramjet
- Engine #12 - Supercharged Ejector Scramjet
- Engine #20 - Ejector ScramLACE (with on-board air liquefaction)
- Engine #22 - Supercharged Ejector ScramLACE
- Engine #32 - Supercharged Ejector ScramLACE using slush hydrogen for LACE

The increasing engine numbers are indicative of increasing engine complexity; higher installed engine weight and lower thrust to weight ratio. The engine increased complexity and weight provides significant increases in Air Augmented Rocket mode specific impulse.

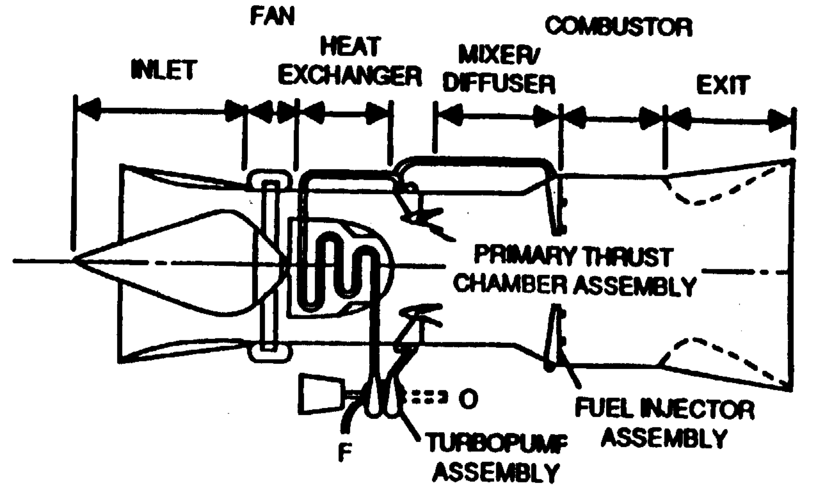
SELECTED RBCC ENGINE TYPES INVESTIGATED

5 - Variants Evaluated

Advanced LACE-Based Propulsion

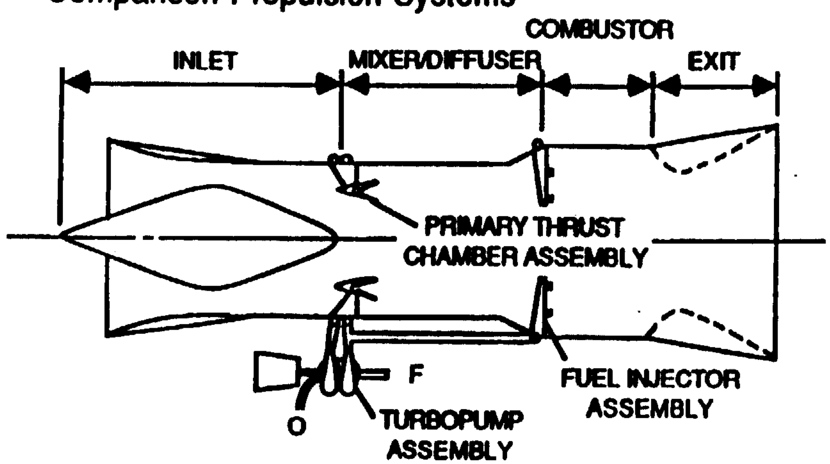


ScramLACE

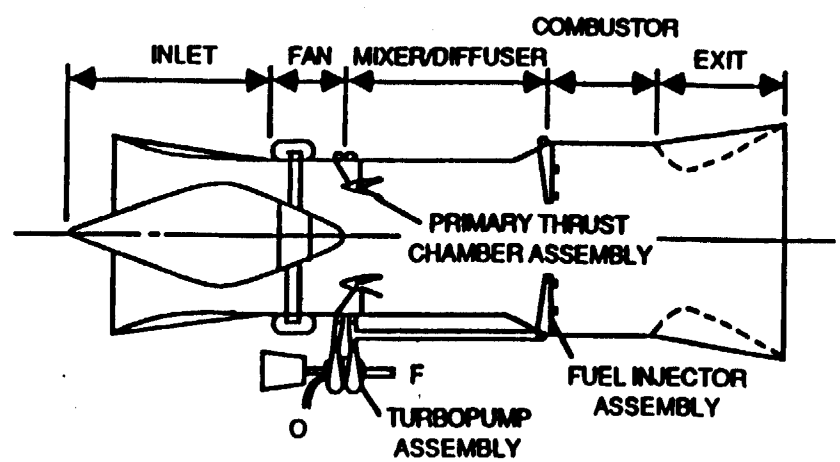


Supercharged ScramLACE
(Both Recycled and Non-Recycled)

Advanced Non-LACE Comparison Propulsion Systems



Ejector Scramjet



Supercharged Ejector Scramjet

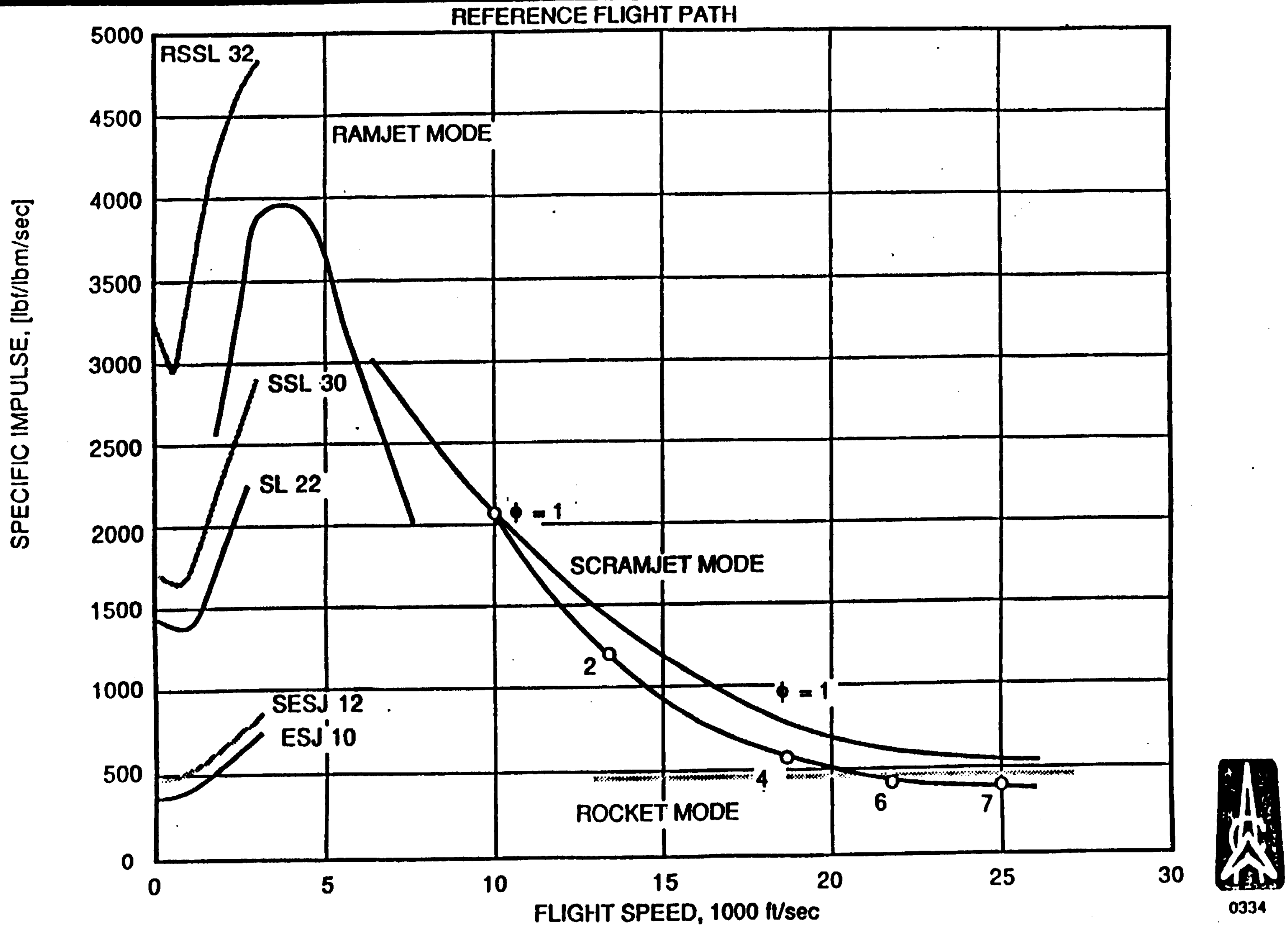
0655

SPECIFIC IMPULSE OVER THE ASCENT PROFILE BY ENGINE AND OPERATING MODE

All five engine types operate with the same ramjet, scramjet and final rocket mode in the SSTO mission. The difference between each of the five types is found only in the air augmented rocket ejector mode used at the start of flight from Mach 0 to Mach 3.5.

The superiority of the more complex engines using liquid air is clearly apparent in the air augmented rocket mode. However, we must consider the performance of each of these engine types over the full SSTO trajectory. We will present ACA's findings on full SSTO trajectory performance in the pages that follow.

SPECIFIC IMPULSE OVER THE ASCENT PROFILE BY ENGINE AND OPERATING MODE.



ROCKET ENGINE SPECIFIC IMPULSE CALCULATION

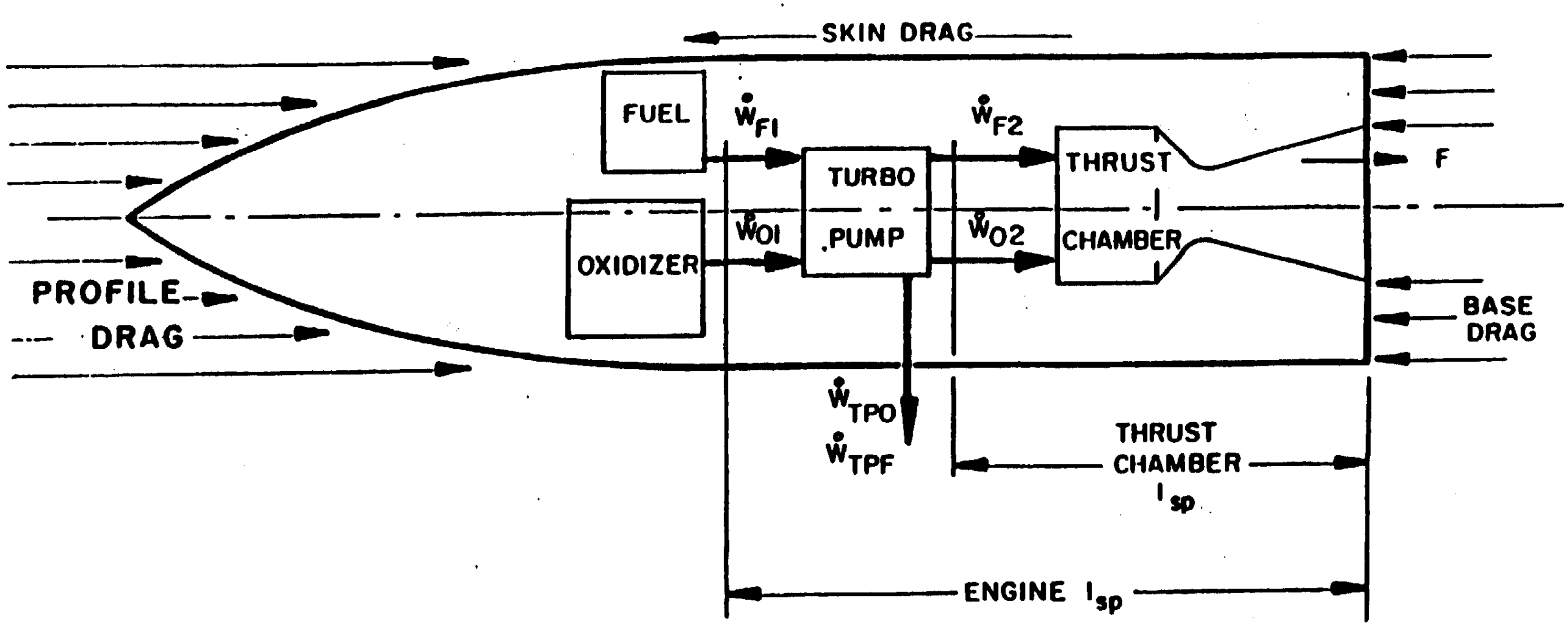
We need to go back to the basics very briefly.

The final velocity of any rocket system is directly proportional to the specific impulse in vacuum.

Rocket thrust chamber specific impulse is calculated by dividing the thrust produced by the engine in lbf by the mass flow rate of oxidizer and fuel to the thrust chamber in lbm/sec. Overall engine specific impulse divides that same thrust by the mass flow rate of oxidizer and fuel to all propellant driven accessories needed to operate the engine plus the mass flow rate to the thrust chamber.

Neither rocket thrust chamber or rocket engine specific impulse include ram or profile drag, skin drag or base drag which must be separately determined together with gt losses, gravity vector value along the flight path x time, to determine the "effective" specific impulse for the rocket engine system operating in a vehicle flying a given trajectory in the atmosphere.

ROCKET ENGINE SPECIFIC IMPULSE CALCULATION



1037

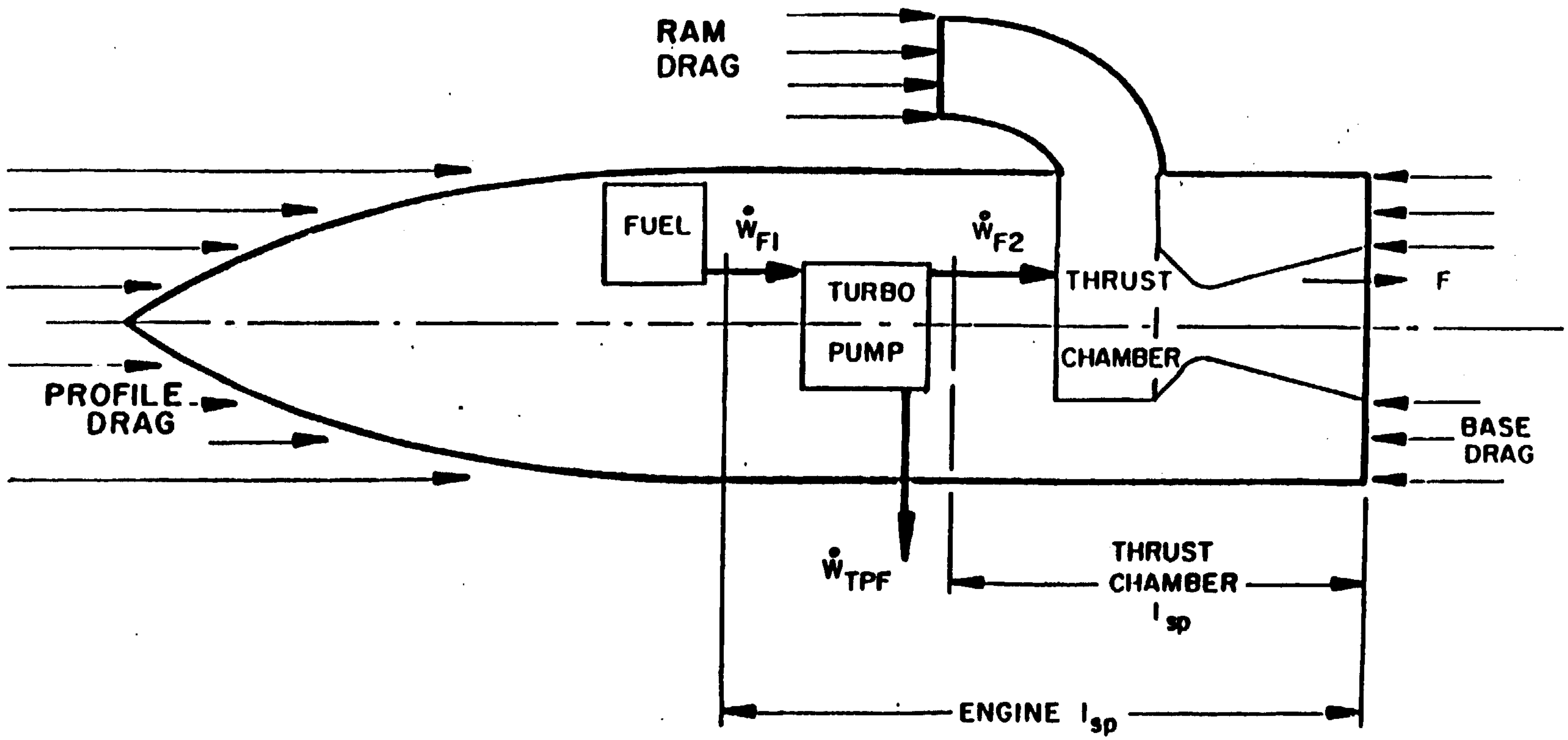
AIR-BREATHIING ENGINES NET JET SPECIFIC IMPULSE CALCULATIONS

In air breathing engines in aircraft applications, the first significant difference in Specific Impulse calculation in comparison to the rocket case is that no oxidizer weight is involved.

The second significant difference is that the ram drag of the engine inlet is subtracted from the gross engine thrust as it would be measured in the rocket case. Thus the thrust value used is the "net" value of gross engine thrust minus inlet drag force. "Net Jet Thrust" of airbreathing engines is specific to flight altitude and velocity; it is not a constant value as in the rocket case.

The remaining vehicle ram drag, skin drag, base drag and gravity losses must be determined for the specific trajectory flown by the vehicle.

AIR-BREATHING ENGINES NET JET SPECIFIC IMPULSE CALCULATION



1038

NET JET SPECIFIC IMPULSE OVER AN SSTO TRAJECTORY FOR AN EJECTRO SCRAMJET RBCC ENGINE

The far right column presents the net jet thrust based specific impulse of an Ejector Scramjet engine. Thus these values are gross thrust minus inlet ram drag incurred at the flight velocity and altitude conditions presented in the far left columns and are corrected for precompression on the vehicle forebody at these same altitude and velocity conditions using a 6 degree wedge to approximate an 8 degree cone forebody used in ACA's study.

These values are based on both theoretical calculation and experimental verification up to Mach 6. The scramjet values used have been reviewed by a number of persons working in this field in a variety of agencies and have been described as being "reasonable to slightly conservative". The rocket mode Isp values are not net jet but are computed on the rocket basis discussed in the second previous chart based on high altitude expansion of demonstrated hydrogen/oxygen rocket engine systems.

NET JET SPECIFIC IMPULSE OVER AN SSTO TRAJECTORY FOR AN EJECTOR SCRAMJET RBCC ENGINE

ENGINE 10 SPECIFIC IMPULSE PROFILE FOR REFERENCE TRAJECTORY
(FOR A 250 klbf SLS ENGINE)
DAVID L. DOUGHTY

15 JUNE 87

REFERENCE TRAJECTORY			SPECIFIC IMPULSE, Isp (lbf-s/lbm) **								
MACH NUMBER (--)	ALTITUDE * (ft)	q+ (psf)	EJECTOR	NO PRESS FIELD RAMJET	4 DEG WEDGE RAMJET	6 DEG WEDGE RAMJET	8 DEG WEDGE RAMJET	@ SCRAMJET	ROCKET	REFERENCE Isp ## PROFILE	ENGINE OPERATING MODE
0.0	0	0	430							430	EJECTOR
0.5	1000	300	430							430	-
1.0	3000	1250	470							470	-
1.5	16000	1750	545	2600						545	-
2.0	30000	1750	640	3350						640	-
2.5	41500	1700	715	3740						715	-
2.9	48300	1660	771	3880						771	-
3.0	50000	1650		3920	3770	3700	3630			3700	RAMJET
3.5	57500	1600		3930	3825	3765	3705			3765	-
4.0	63000	1500		3800	3730	3685	3640			3685	-
4.5	68000	1500		3610	3570	3535	3500			3535	-
5.0	72500	1500		3380	3370	3350	3330			3350	-
5.5	76500	1500		3100	3135	3135	3135			3135	-
6.0	80000	1500		2790	2900	2900	2900	3000		3000	SCRAMJET
6.5	83500	1500						2900		2900	-
7.0	86500	1500						2750		2750	-
7.5	89500	1500						2625		2625	-
8.0	92000	1500						2500		2500	-
8.5	95000	1500						2400		2400	-
9.0	97500	1500						2300		2300	-
9.5	100000	1500						2175		2175	-
10.0	102000	1400						2050		2050	-
11.0	115000	1300						1725		1725	-
12.0	120000	1000						1450		1450	-
13.0	130000	900						1225		1225	-
14.0	135000	800						1025		1025	-
15.0	140000	750						850		850	-
16.0	145000	700						750		750	-
17.0	155000	600						650		650	-
18.0	160000	500						550		550	-
19.0	165000	450						525		525	-
20.0	175000	400						475	470	470	ROCKET
21.0		350						450	470	470	-
22.0		250						425	470	470	-
23.0		200						400	470	470	-
24.0		100						400	470	470	-
25.0		50						400	470	470	-
26.0								375	470	470	-
27.0									470	470	-

* AIAA-86-1308
\+ STAARS DATABASE #0211, CAPTURE AREA/CAPTURE AREA @ M-25
\# 57.0 ft DIAMETER VEHICLE, 70% CAPTURE AT M-25
@ STAARS DATABASE # TBD, PRELIMINARY ENGINE INFORMATION ON FIVE COMBINED CYCLE ENGINES
** A STUDY OF COMPOSITE PROPULSION SYSTEMS FOR ADVANCED LAUNCH VEHICLE APPLICATIONS, VOLUME 6
!! A STUDY OF COMPOSITE PROPULSION SYSTEMS FOR ADVANCED LAUNCH VEHICLE APPLICATIONS, VOLUME 4, PAGE 23
\## ASSUMES 6-DEGREE 2-DIMENSIONAL WEDGE INDUCED PRESSURE FIELD, EJECTOR MODE SHIFT TO RAMJET MODE AT MACH 3, RAMJET MODE SHIFT TO SCRAMJET MODE AT MACH 6, SCRAMJET MODE SHIFT TO ROCKET MODE AT MACH 20

1041

AXISYMMETRIC VEHICLE AT 100% CAPTURE

RBCC engines can be designed to power a vehicle in the configuration illustrated on the facing chart.

In this configuration, the only difference between the Net Jet Specific Impulse Values presented on the preceding page and those encountered in flight are losses due to skin drag over the engine circumferential area and gravity losses.

Ram drag losses, over 100% of the frontal area, are already included in the previous Net Jet Isp values presented on the previous chart. With the exhaust jet completely wetting the aftbody, there is no base drag loss.

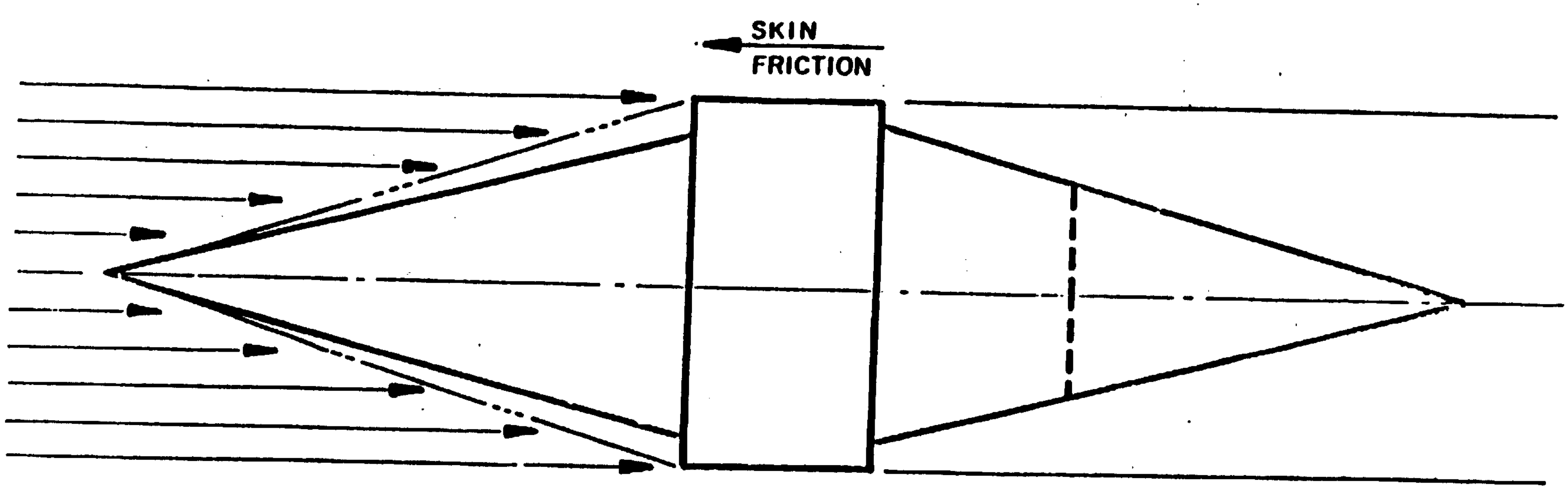
This condition is an instantaneous condition that occurs at termination of scramjet propulsion and immediately before transition to rocket mode in the systems studied by ACA.

The aftbody cone need not be configured as shown. It may be terminated as indicated by the dotted line and the remaining flow volume will fill with recirculating exhaust gases to produce the same zero base drag condition.

The condition illustrated is, as noted, an instantaneous one. However, it is approached progressively over the full trajectory and the benefits of this configuration realized over the full trajectory are significant.

In the ACA study, a value of 70% capture was used at the "shock-on-lip" condition - not the ideal value of 100%. The 70% figure is based on past hardware performance of real inlet systems.

AXISYMMETRIC VEHICLE AT 100% CAPTURE



1039

CAPTURE AREA FOR NON-AXISYMMETRIC AND AXISYMMETRIC VEHICLES

In otherwise directly comparable vehicles, non-axisymmetric configurations do not achieve the performance of axisymmetric configurations. Additional ram or profile drag losses are incurred.

Both configurations will incur all aerosurfaces ram and skin drag and induced drag due to lift. Neither has an advantage or disadvantage in this respect.

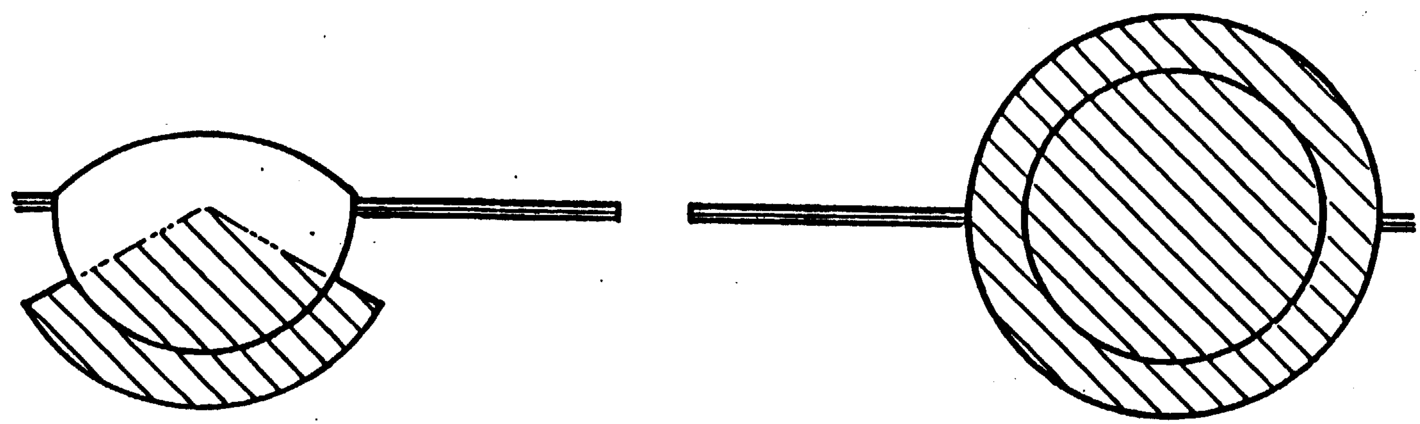
A NOTE ON STRUCTURAL COMPLEXITY AND COST

Axisymmetric vehicle structures, i.e., structures constructed in a manner similar to ballistic rocket systems, have fewer and simpler unique structural elements and many identical structural elements.

Non-axisymmetric vehicles, i.e., aircraft like, have many unique structural elements. This is exemplified by the SHUTTLE structure which is composed of approximately 70% uniques structural pieces for the upper left, lower left, upper right and lower right portions of its structure.

Axisymmetric vehicle design should be expected to provide significantly reduced design engineering costs, structural tooling costs and reduced structure parts count.

CAPTURE AREA FOR NON-AXISYMMETRIC AND AXISYMMETRIC VEHICLES



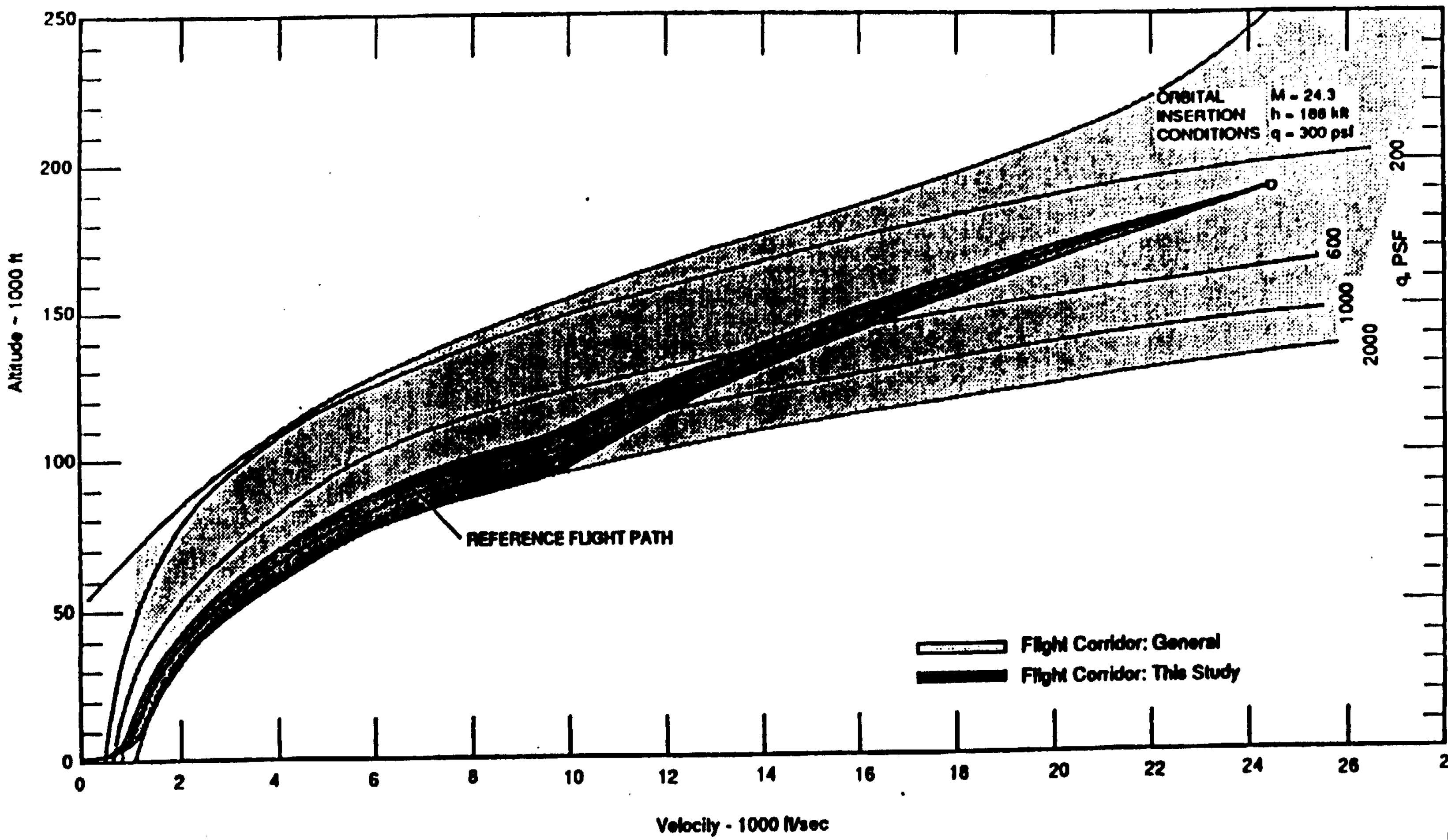
1040

REFERENCE ASCENT FLIGHT PATH

The trajectories studied by ACA include both a constant q path at 1500 psf to local orbital velocity followed by a Hohmann transfer to 100 mile circular orbit and a 1500 psf constant q path to Mach 10 followed by an equilibrium radiation cooled wall temperature path to local orbital velocity and a Hohmann transfer to the 100 mile circular orbit.

The performance on the equilibrium path, in terms of payload delivered, was superior to the constant q path. However, other considerations such as limiting angle of attack on the forebody, might, with further study, be shown to be the optimum.

REFERENCE ASCENT FLIGHT PATH



APPROACH TO TRAJECTORY SIMULATION USED

The objective of the six charts that follow is to show that the trajectory analysis work performed by ACA was extensive and detailed.

The trajectory analysis program used by ACA and MMDA was developed by AFWAL/POPA at WPAFB and is known as DOF36. DOF36 was used to analyze all five variations of the RBCC engines previously illustrated for orbital trajectories with aerodynamic characteristics and propulsion system characteristics defined an .5 Mach number intervals to Mach 10 and full mach number intervals to local orbital velocity. DOF36 provided finer analysis by interpolation between these values in the course of operation of the program.

Aerodynamic characteristics for the vehicle configuration studied were determined jointly by Martin Marietta Space Division and ACA staff. These characteristics were determined for all forms of drag, drag induced by lift and lift for the studied vehicle at angles of attack of +/- 18 degrees.

The engine performance tables used were developed for each of the five engines over the reference trajectory and an example for Engine 10 was presented in the preceding chart.

Well over 400 trajectory simulation runs were made in the course of study.

APPROACH TO TRAJECTORY SIMULATION USED

1. Select gross weight, engine and lifting surface size class

2. Estimate vehicle diameter over the engines

3. Select the appropriate Aero Table from 4 Strake Types

4. Select appropriate Engine Table from 5 engine types

5. Perform trial runs to achieve compliance to the Reference or other Trajectory Requirements in terms of Mach No. vs Altitude

6. When compliance is achieved, a run is made to establish the first calculated Mass to Orbit, M2, and the propellant mass requirements

7. Using an ACA program, Oxidizer and Hydrogen Volume requirements are calculated for each engine type

8. Using an MMDA program, the structural geometries and weight estimates are made

9. If the aerodynamic reference dimension, the diameter over the engines, produced by the MMDA program, which includes Hohmann transfer propellants, RCS propellant, Retrofire and Boiloff and Reserves, are more than 3% different from the initial estimate in 2. above, the simulation is rerun with the new diameter. Otherwise, the run is accepted

10. When the run is accepted as a valid trajectory simulation, the MMDA program generated weight estimate is also accepted.

11. The MMDA program generated weights and geometries include VEHICLE STRUCTURE WEIGHT, Hohmann transfer Propellants, RCS Propellant, Retrofire and Boiloff and Reserves. These weights are subtracted from M2 determined in 9. above. This yields the mass available for flyback propellant and discretionary payload

0605

TABULAR OUTPUT - REPORT 1

DOF36 provided a detailed tabular output of the performance of the vehicle over the full trajectory.

Gamma	Flight Path Angle
Alpha	Angle of Attack
W-Dot	Propellant Mass Flow Rate
Isp	Net Jet Isp
Ieff	Net Jet Isp minus drag and gt losses
Irat	Ratio of Isp/Ieff
GCB-1	Longitudinal Acceleration

TABULAR OUTPUT - REPORT 1

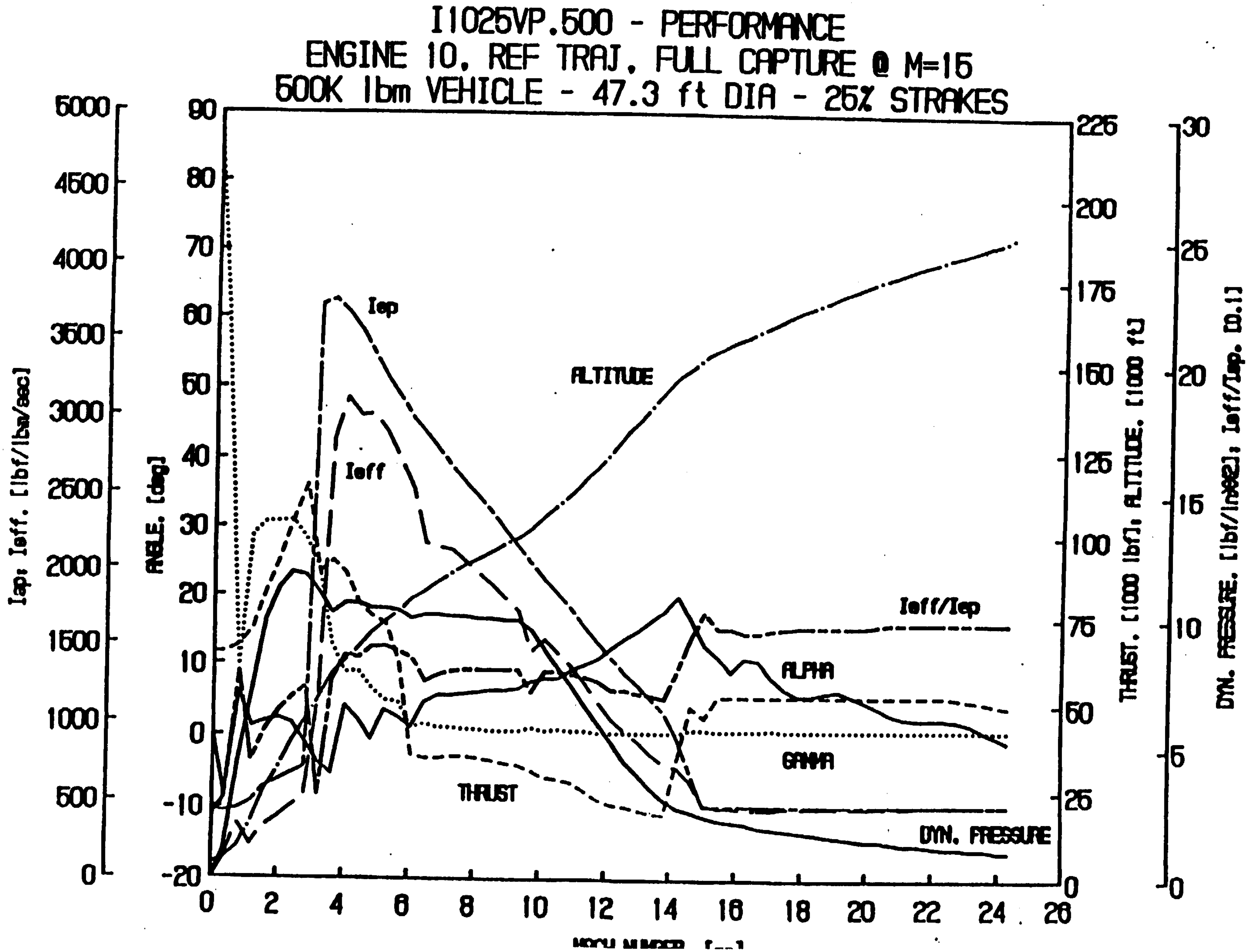
```
1        6 D - O - F   S U M M A R Y   O U T P U T
0     RUN TITLE:  ENGINE 32, REF HOR TRAJ/ISP/FFMAX, ACA AERO - 16 deg - 59.5 ft DIA - 10% STRAKE
0                    AERODYNAMIC FILE ----- A321016V.611
0                    ENGINE FILE ---------- E32REFH.615
0                    INPUT FILE ----------- I3210HP.623
0                    SUMMARY FILE --------- O3210HP.623


+++++ RUN SUMMARY +++++
 ENGINE 32, REF HOR TRAJ/ISP/FFMAX, ACA AERO - 16 deg - 59.5 ft DIA - 10% STRAKE
 TERMINATION CONDITION = 101
      FINAL CONDITIONS:
      TIME=   1005.48      ALT =  187986.6      MACH=     24.31
      M1  = 956000.00      M2  = 353468.59      MR  =    2.7046
      ISPE=    806.59      ISPA=   1271.17      ISPT=  0.7659200000E+09

1/////      D - 0 - F   OUTPUT SUMMARY   /////                 PAGE   1
```

TIME	ALTITUDE	MACH	SPEED	Q	GAMMA	ALPHA	WEIGHT	W-DOT	ISP	THRUST	IEFF	IRAT	GCB-1
0.00	0.0	0.00	1.0	0.00	0.00	0.00	956000.00	3100.00	3319.6	1311240.6	0.0	0.00	1.37
5.00	0.0	0.19	216.2	0.39	0.00	0.78	954051.56	383.04	3242.5	1242012.5	3278.1	1.01	1.30
10.00	0.0	0.37	416.1	1.43	0.00	8.82	952171.44	368.86	3170.9	1169629.9	3149.3	0.99	1.22
15.00	0.0	0.52	576.4	2.74	0.79	16.36	950348.00	392.46	3131.1	1228843.6	2599.5	0.83	1.27
20.00	311.4	0.62	694.8	3.95	11.19	16.02	948377.69	395.45	3203.7	1266910.6	1773.4	0.55	1.30
25.00	1445.4	0.70	776.3	4.77	24.48	13.53	946394.94	397.57	3255.3	1294213.7	1210.4	0.37	1.31
30.00	3491.7	0.77	852.8	5.42	35.02	9.58	944402.00	399.65	3305.9	1321211.5	1128.0	0.34	1.33
35.00	6270.7	0.86	938.9	6.04	41.21	4.96	942397.75	402.08	3364.7	1352889.9	1260.1	0.37	[illegible]
36.92	7499.6	0.90	973.1	6.24	42.31	3.17	941623.69	399.86	3388.7	1355000.[illegible]	[illegible]		
36.92	7499.6	0.90	973.1	6.24	42.31	3.17	941623.69	399.86	[illegible]	[illegible]			
39.00	8882.9	0.93	1011.2	6.46	41.73	2.18	940785.[illegible]	[illegible]					
44.00	12281.8	1.03	1105.1	6.93	38.31	[illegible]							
49.00	15867.4	1.15	[illegible]	[illegible]									
54.00	[illegible]												

0811

DOF36 GRAPHICAL OUTPUT OF MAJOR PERFORMANCE PARAMETERS OVER THE REFERENCE TRAJECTORY - PLOT NO. 1

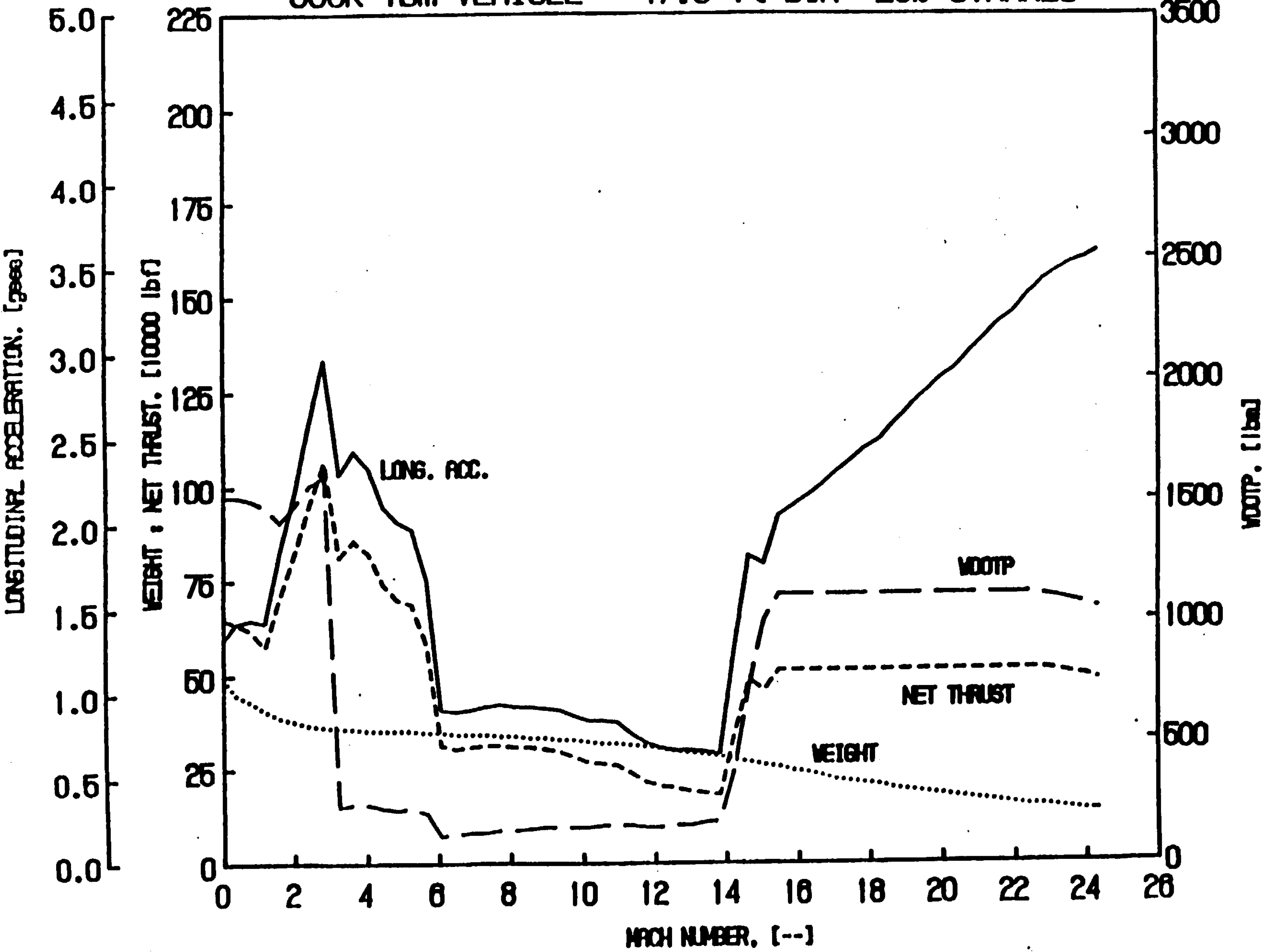
DOF36 was interfaced with a plotter to produce two graphical outputs of vehicle performance over the full trajectory. In the output presented here, the major vehicle performance measures are plotted.


I1025VP.500 - PERFORMANCE
ENGINE 10, REF TRAJ, FULL CAPTURE @ M=15
500K lbm VEHICLE - 47.3 ft DIA - 25% STRAKES
Iap, Ieff, [lbf/lbm/sec]
ANGLE, [deg]
THRUST, [1000 lbf], ALTITUDE, [1000 ft]
DYN. PRESSURE, [lbf/in**2], Ieff/Iap, [0.1]
Iep
Ieff
ALTITUDE
Ieff/Iep
ALPHA
GAMMA
THRUST
DYN. PRESSURE
0
2
4
6
8
10
12
14
16
18
20
22
24
26
-20
-10
0
10
20
30
40
50
60
70
80
90
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
25
50
75
100
125
150
175
200
225
0
5
10
15
20
25
30

DOF35 GRAPHICAL OUTPUT OF MAJOR PERFORMANCE PARAMETERS OVER THE REFERENCE TRAJECTORY - PLOT NO. 2

The second graphical output presented the weights and forces variation over the full trajectory. In the example illustrated here, transition from scramjet mode to rocket mode occurs at Mach 15. This transition point was found to be an optimum as will be discussed further. This optimization characteristic was a major finding of the ACA study.

I1025VP.500 - WEIGHTS & FORCES
ENGINE 10, REF TRAJ, FULL CAPTURE @ M=15
500K lbm VEHICLE - 47.3 ft DIA -25% STRAKES



MMDA WEIGHT, SIZING AND C.G. ANALYSIS

Based on their in-house experience with launch vehicle structures, Titan IV and STAS related analyses, MMDA developed weight estimations for the structural elements

Propulsion system weight estimates were developed by ACA.

Both groups of weight estimation data assumed current technology and the reductions expected to be achieved by 1995 which was the development start date target for the study.

Vehicle Sizing Data for 1995

Vehicle Name: Strawman 1 Configuration :S105015V.500

Program Name: Air Augmented Rocket

Date: 12-03-1987

Nose Cone Data:

Length = 9.8'
Nose Cap Radius = 1'
Major Outside Diameter = 4.5'
Wetted Area = 98 sqft
Structure Weight = 179 lb
C.G. = Sta 67.4

Crew Compartment Data:

Length = 17.8'
Minor Outside Diameter = 4.5'
Major Outside Diameter = 9.5'
Wetted Area = 393 sqft
Structure Weight = 719 lb
C.G. = Sta 237.3

Fixed Weight = 3,000 lb
C.G. = Sta 190.5

Crew Weight = 440 lb
C.G. = Sta 292.9

Oxidizer Area Data:

Length = 30.2'
Minor Outside Diameter = 9.5'
Major Outside Diameter = 18.0'
Wetted Area = 1,316 sqft
Structure Weight = 2,408 lb C.G. = Sta 531.1

Tank Weight = 531 lb C.G. = Sta 596.5

Oxidizer Weight = 258,011 lb C.G. = Sta 604.1

Tank Insulation Weight = 1,602 lb C.G. = Sta596.5

Small Dome Height = 3.5'
Small Dome Diameter (I.D.) = 10.0'
Tank Frustum Length = 21.0'
Large Dome Height = 5.6'
Large Dome Diameter (I.D.) = 15.9'

Tank Volume = 3,741 cuft

Configuration :S105015V.500 Page 2

Fuel Area Data:

Length = 82.6'
Minor Outside Diameter = 18.0'
Major Outside Diameter = 33.6'
Surface Area = 6,842 sqft
Structure Weight = 12,521 lb C.G. = Sta 1233.7

Tank Weight = 4,018 lb C.G. = Sta 1175.1

Fuel Weight = 121,359 lb C.G. = Sta 1199.2

Tank Insulation Weight = 8,183 lb C.G. = Sta 1175.1

Small Dome Height = 6.9'
Small Dome Diameter (I.D.) = 19.4'
Tank Frustum Length = 48.7'
Large Dome Height = 16.5'
Large Dome Diameter (I.D.) = 33.1'

Tank Volume = 28,306 cuft

Payload Bay Area:

Length = 10'
Wetted Area = 648 sqft
Structural Weight = 1,186 lb
C.G. = Sta 0.0

Payload C. G. = Sta 1619.1

Engine Area Data:

Engine Type = 10
# of Engines = 8
Total Engine Weight = 40,880 lb C.G. = Sta 1275.4

Strake Area Data:

Strake Length = 58.5'
Surface Area (ea) = 568 sqft
Total Weight = 8,309 lb
C.G. = Sta 749.4

1995 TAD Vehicle Sizing Data with Liquid Hydrogen (cont.)

Configuration :S105015V.500 Page 3

Misc. Component Data:

APU Weight = 5,000 lb C.G. = Sta 78.6

Landing Gear Weight = 10,000 lb C.G. = Sta 1395.6

Wiring Weight = 382 lb

RCS & Control Weight = 454 lb

Overall Vehicle Data:

Length = 140.4'

Tank Structure O.D. = 33.6'
Diameter to Outside of Strakes = 50.4'
Diameter to Outside of Engines = 42.6'
Max. Fuselage Diameter = 50.4'

Nose Cone Angle = 16.0 deg.
Tail Cone Angle = 20.0 deg.

Sizing based on Liquid Fuel

Propellant Weight & Volume Break Down

Fuel:

Ascent	115,505 lb	26,132 cuft
Hohman Transfer	329 lb	74 cuft
ACS	25 lb	6 cuft
Retrofire	351 lb	79 cuft
Boiloff & Resvs	149 lb	34 cuft
Flyback	5,000 lb	1,131 cuft
Total	121,359 lb	27,457 cuft

Oxidizer:

Ascent	252,928 lb	3,557 cuft
Hohman Transfer	1,917 lb	27 cuft
ACS	152 lb	2 cuft
Retrofire	2,122 lb	30 cuft
Boiloff & Resvs	891 lb	13 cuft
Total	258,011 lb	3,629 cuft

Ascent Fuel Weight Includes :
1% Addition for Residuals and Unusable Fluids
1.5% Addition of the Usable Fuel for the APU, RCS, and ECS

1995 TAD Vehicle Sizing Data with Liquid Hydrogen (cont.)

Configuration :S105015V.500 Page 4

Vehicle Weight Summary:

Component Name	Component Weight (lb)
Fuselage & TPS	17,012 lb
Strakes	8,309 lb
Tanks (O2 & H2)	4,549 lb
Insulation	9,785 lb
Fixed	3,000 lb
RCS & Controls	454 lb
Wiring	382 lb
APU	5,000 lb
Engines & Inst	40,880 lb
Landing Gear	10,000 lb
Dry Weight	99,370 lb
Propellant	374,370 lb
Payload	
Net	20,820 lb
Flyback	5,000 lb
Crew	440 lb
Gross Veh. Weight	500,000 lb

Fuel Mass Fraction = 75.9 %
Payload/Glow Ratio = 0.053
Payload/Dry Weight Ratio = 0.264

Dry Weight C.G. = Sta 1064.7
Gross Weight C.G. = Sta 882.1

SENSITIVITIES AND TRADES

1. Payload sensitivity to Takeoff Mode

2. Payload sensitivity to I_{sp} variation by Propulsion Mode and Scramjet Termination Mach Number

3. Payload sensitivity to Mach number and vehicle gross takeoff weight

4. Payload sensitivity to engine type and vehicle gross weights at takeoff

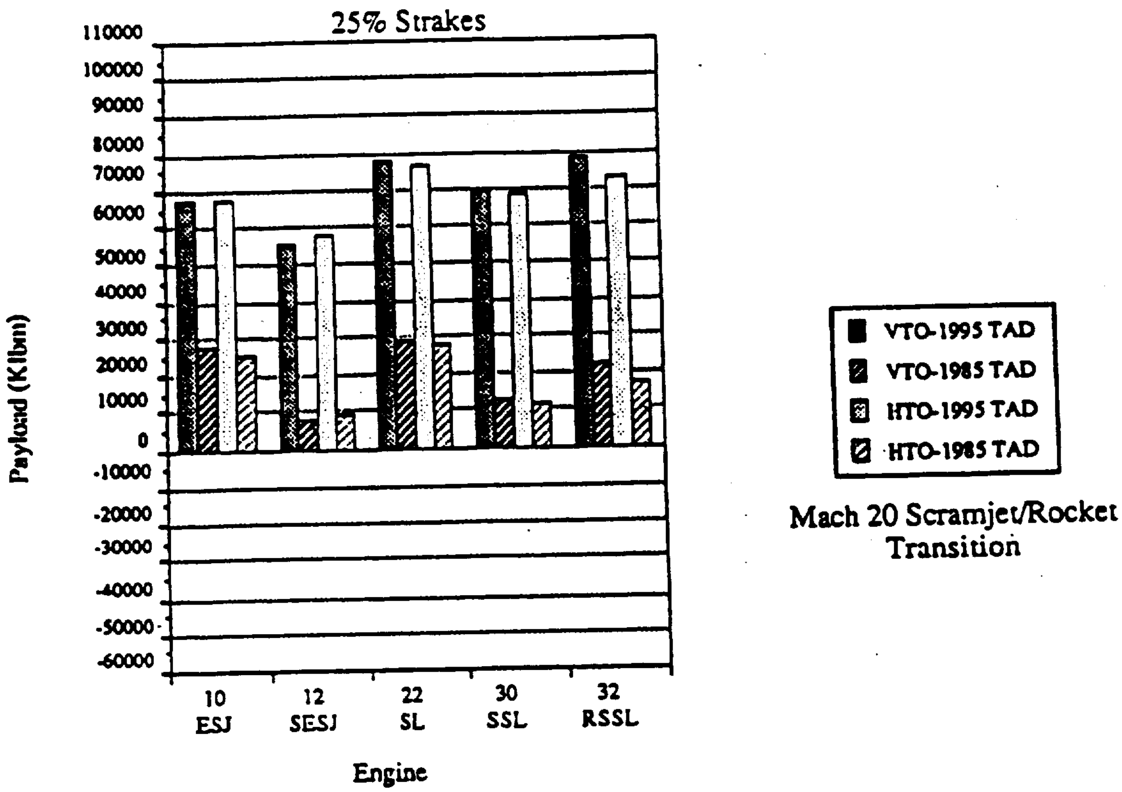
5. Payload sensitivity to inert weight estimates for various engine types and different gross weights at takeoff

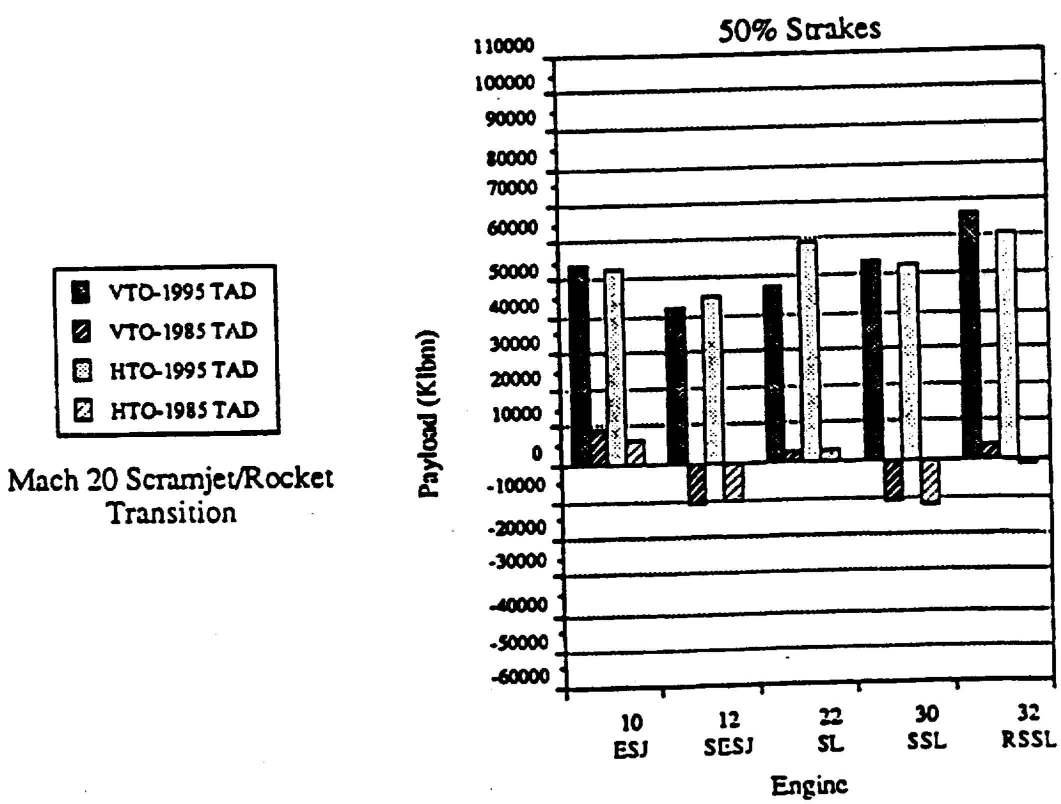
6. Payload sensitivity to the use of Slush Hydrogen

7. Payload sensitivity to drag estimates

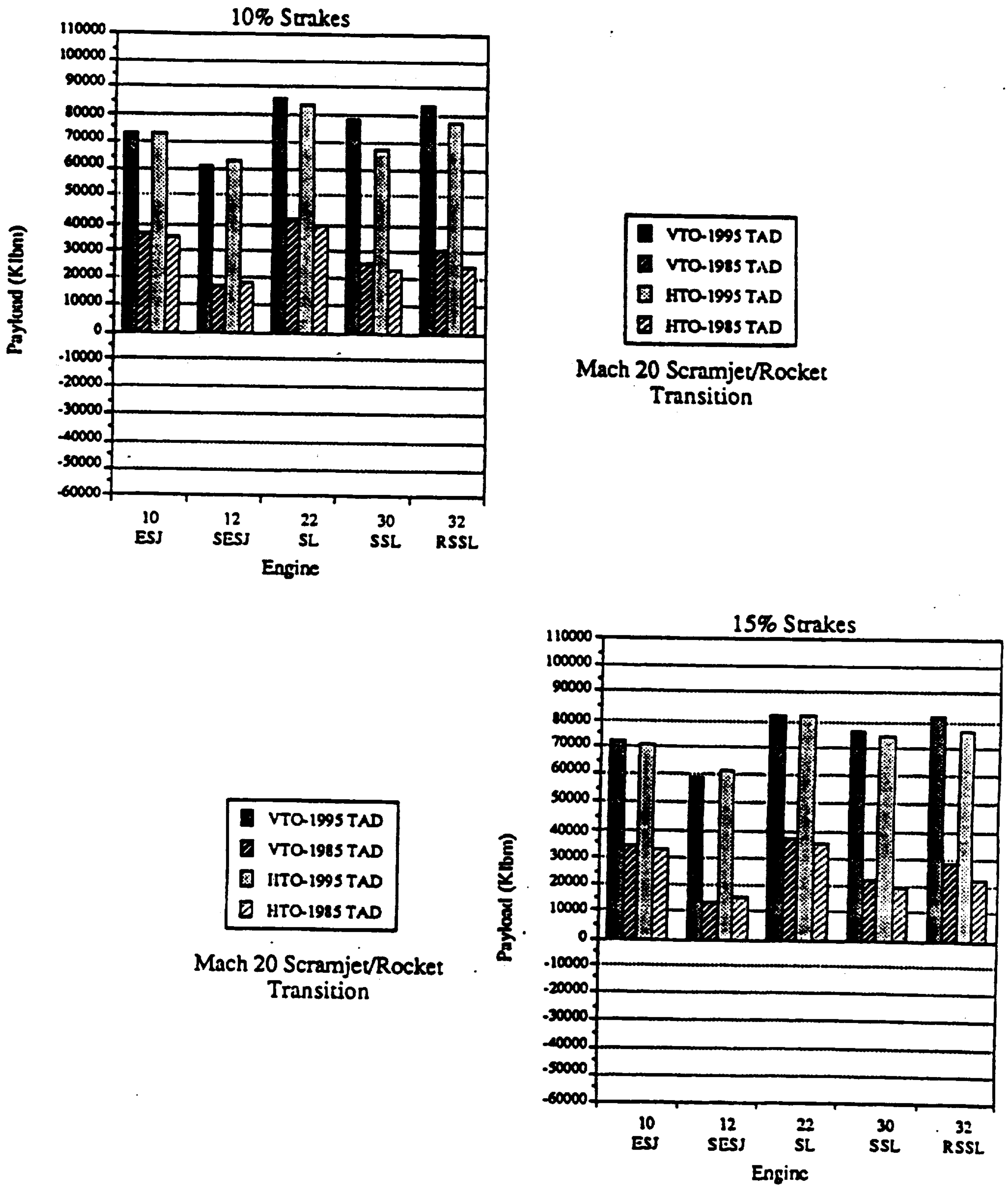
8. Sensitivity of range and endurance to engine type and cruise Mach number.

aai6

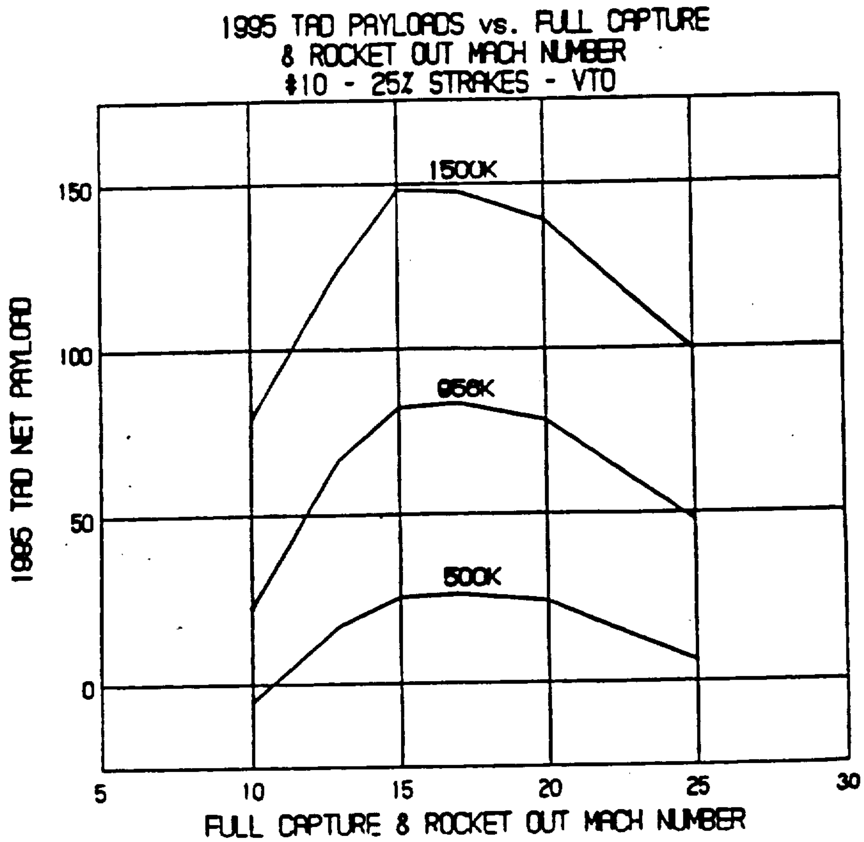




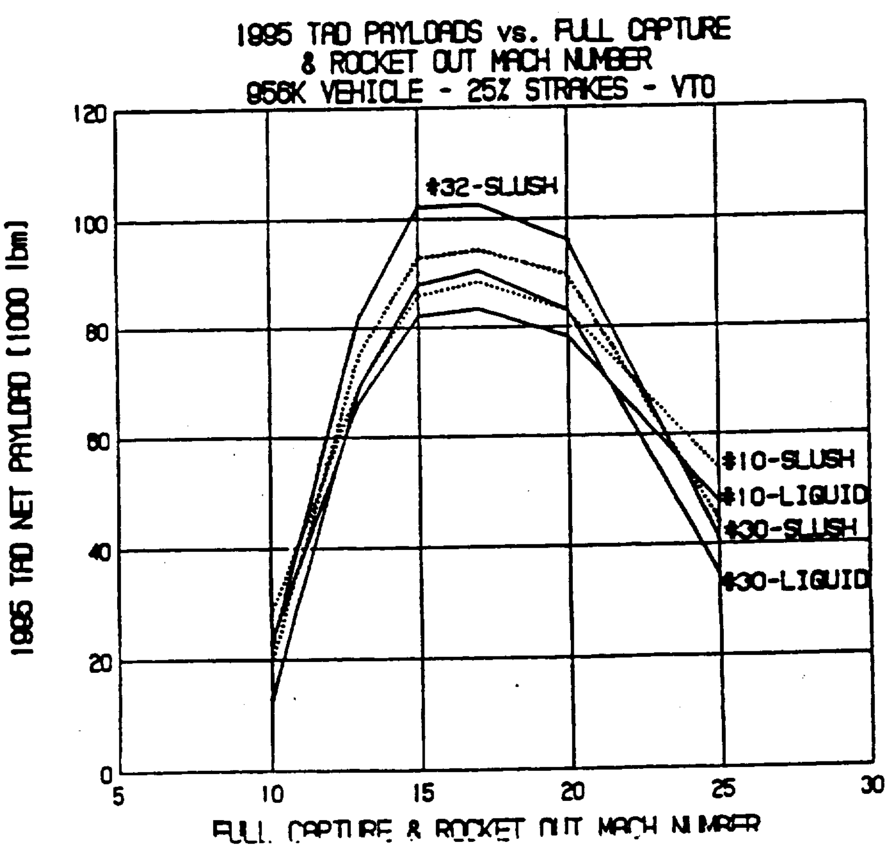
Payload vs. Engine Type and Strake Size for a 956 klbm Vehicle at 20% and 25% Strake Sizes



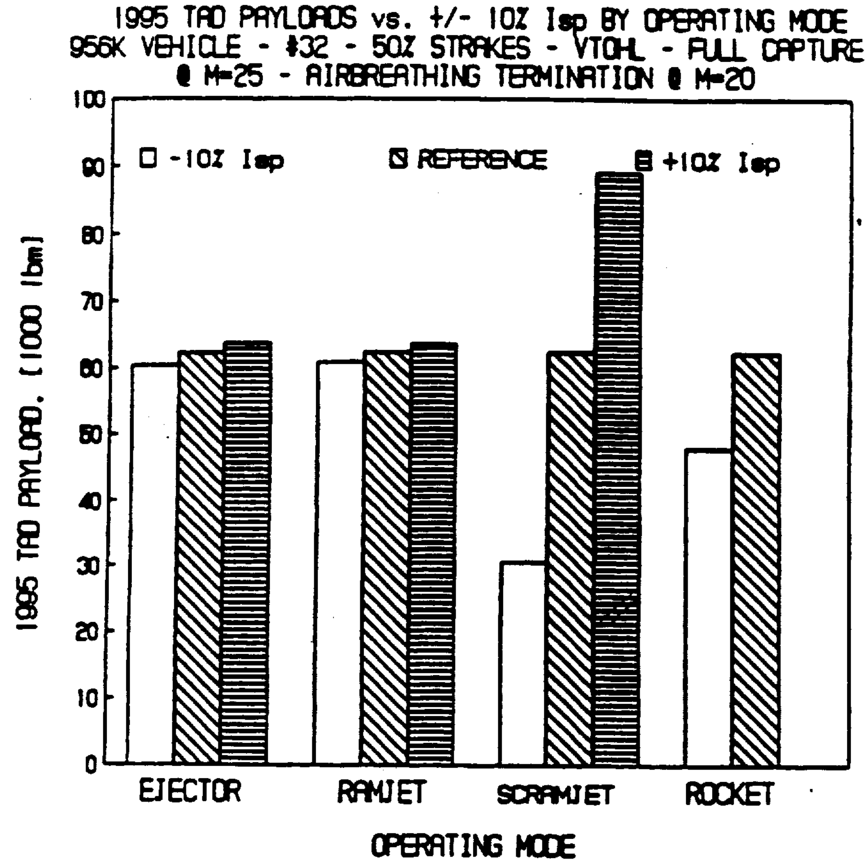
Payload vs. Engine Type and Strake Size for a 956 klbm Vehicle at 10% and 15% Strake Sizes



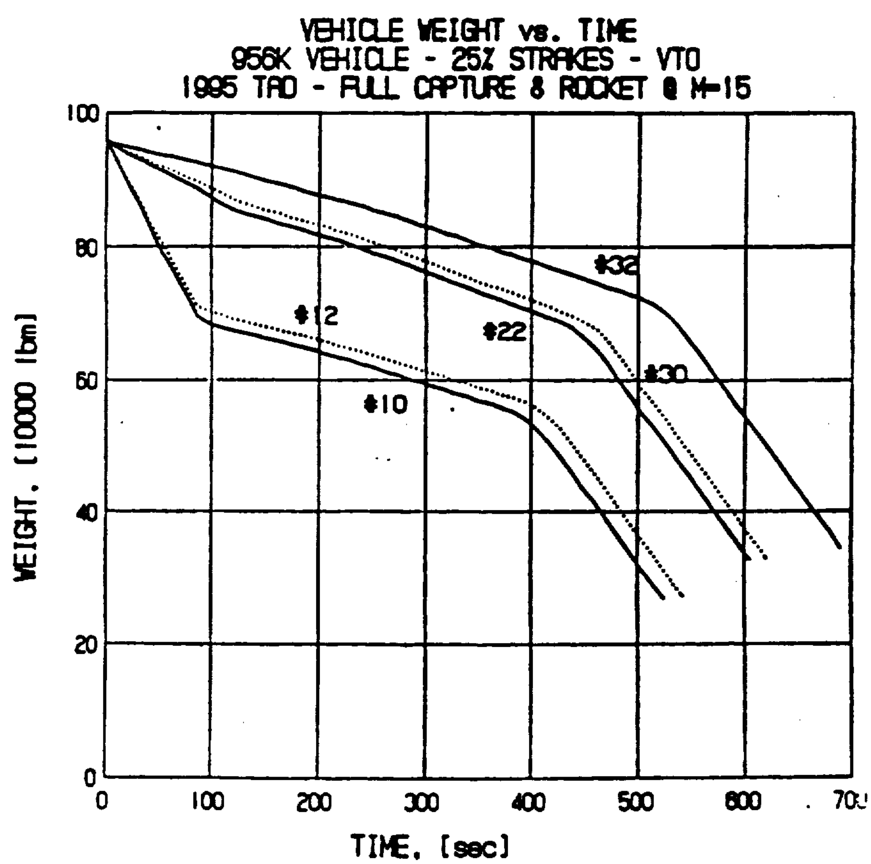
Payload vs. Full Capture and Rocket Out Mach Number for Varying TOGW/GLOW Weight Classes



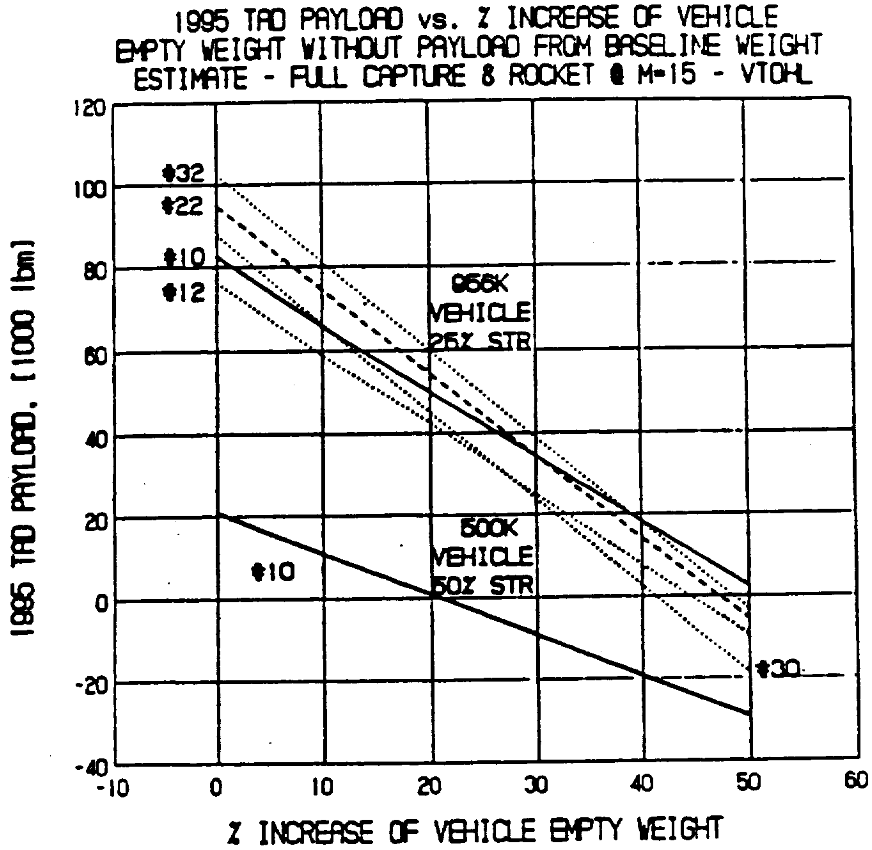
Payload vs. Full Capture and Rocket Out Mach Number for Various Engine Types



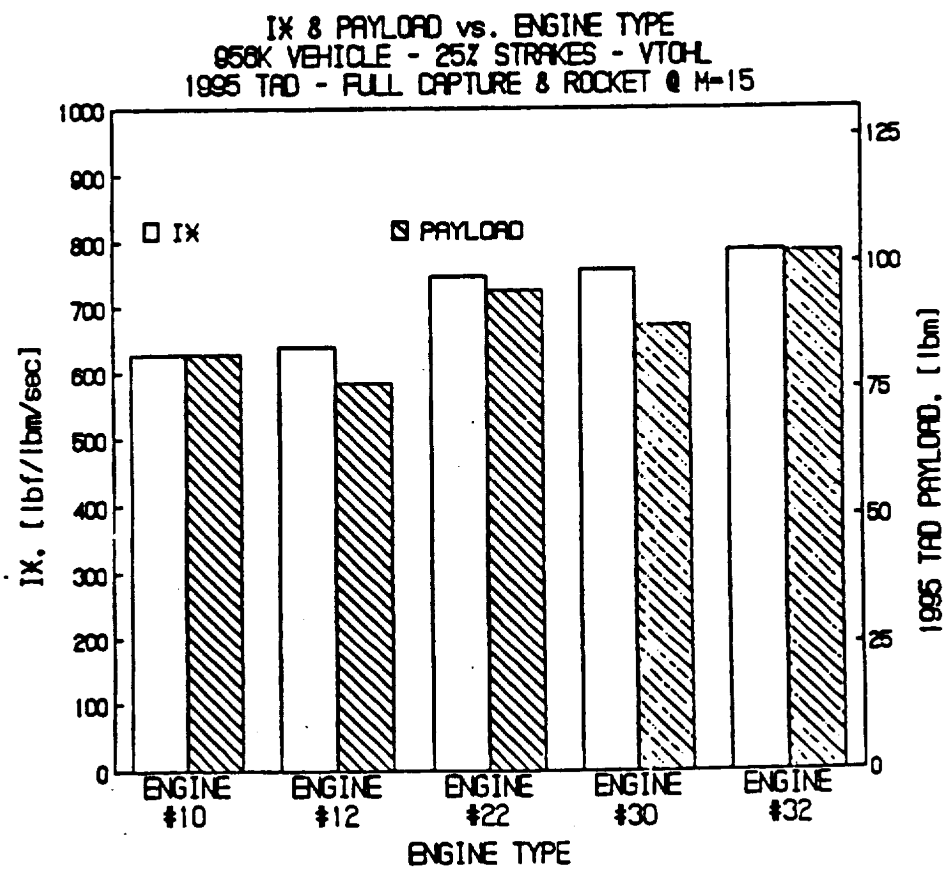
Effect of +/- 10% Isp by Propulsion Mode on Payload



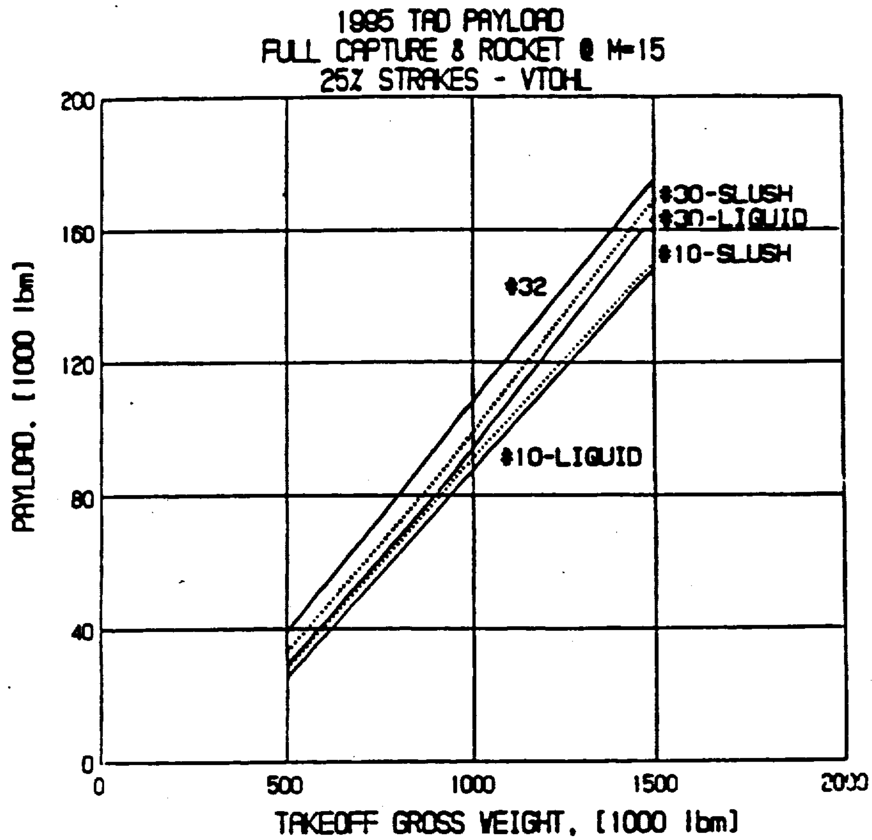
Vehicle Weight History for all Five RBCC Engine Types Studied



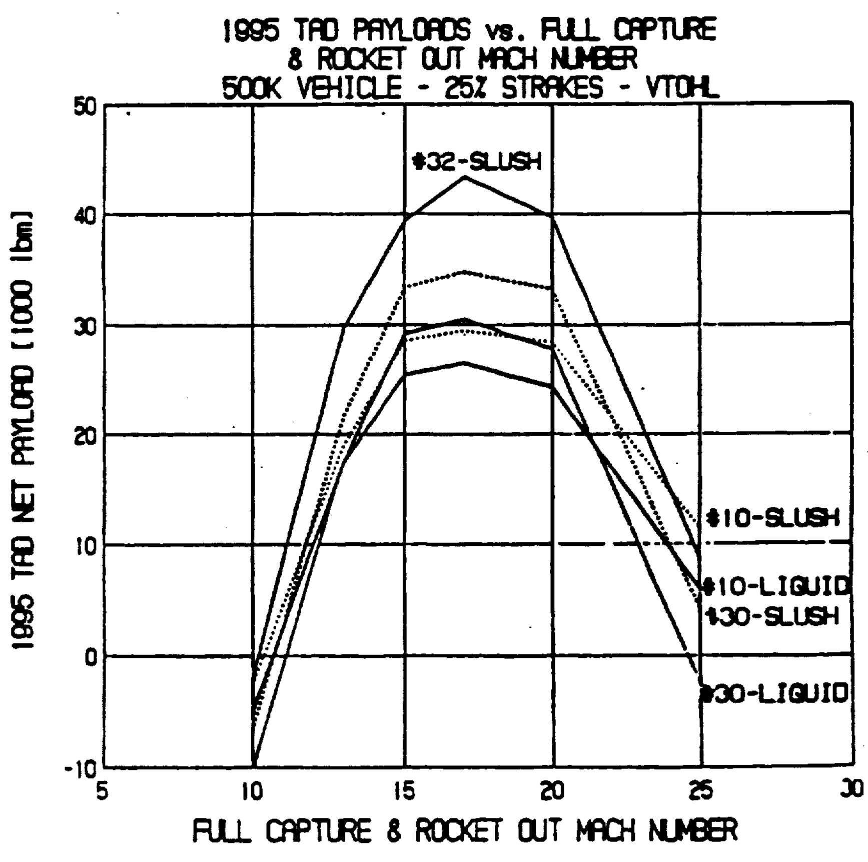
Payload vs. % Variation in Weight Estimates



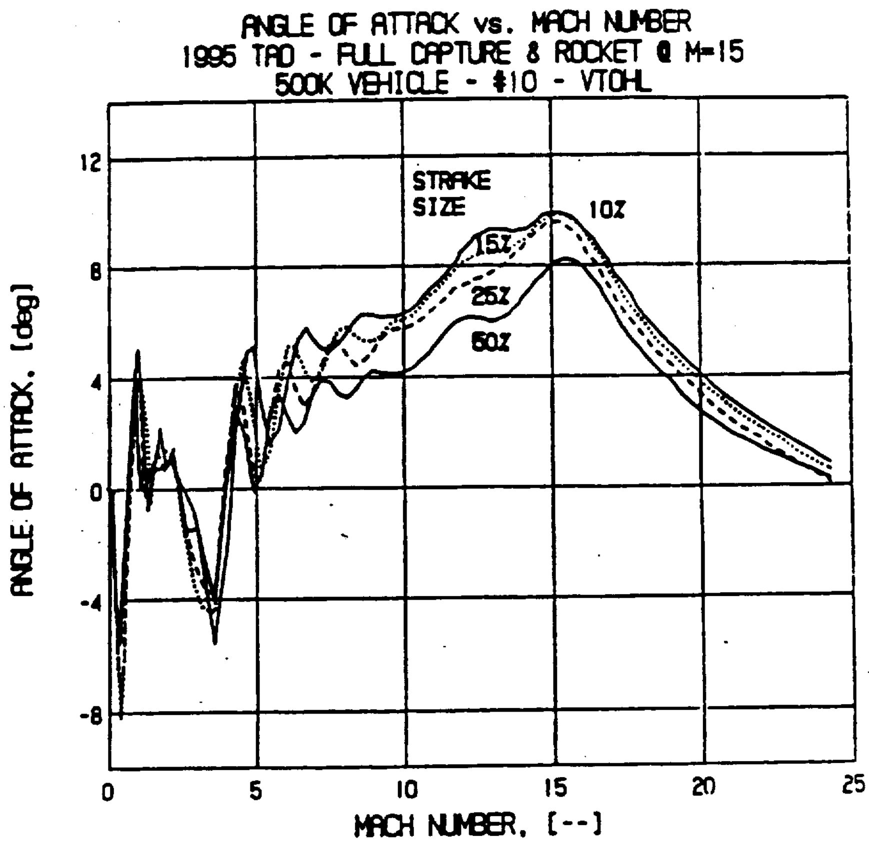
I* and Payload vs. Engine Types



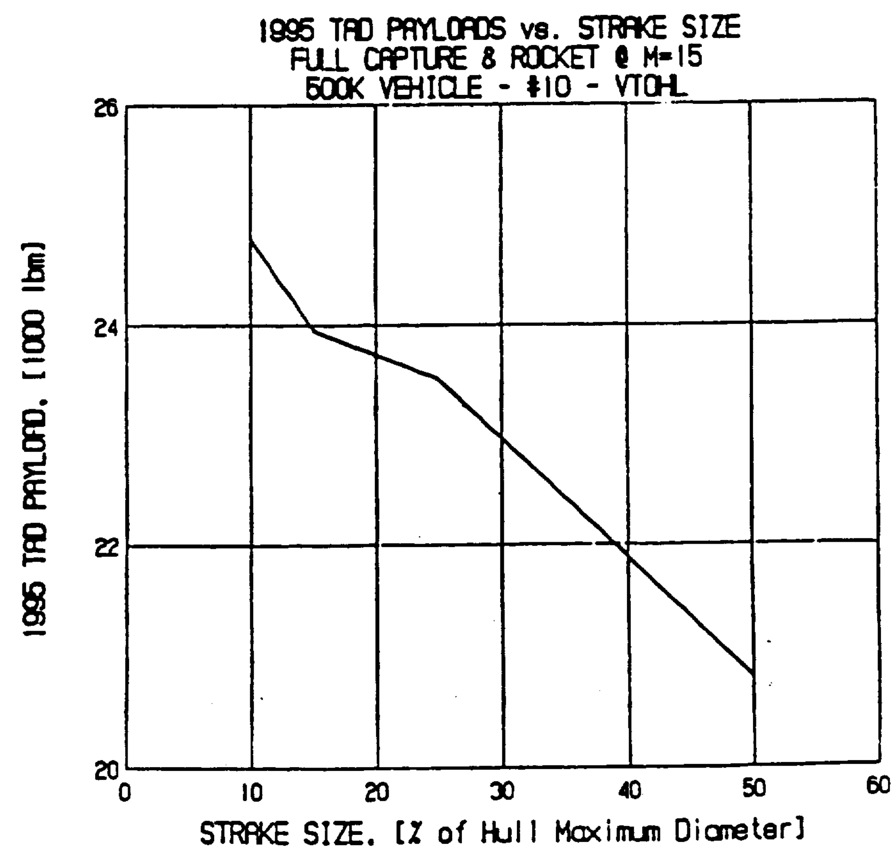
Payload vs. TOGW and Engine Type



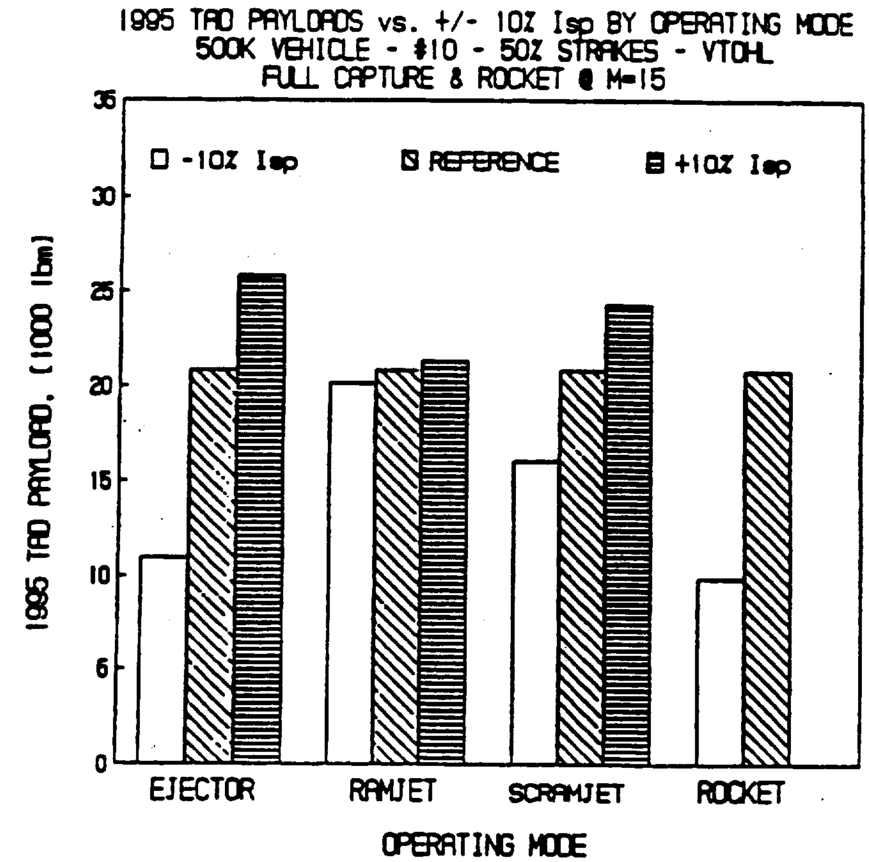
Payload vs. Full Capture Mach Number for Engines #10, #30 and #32



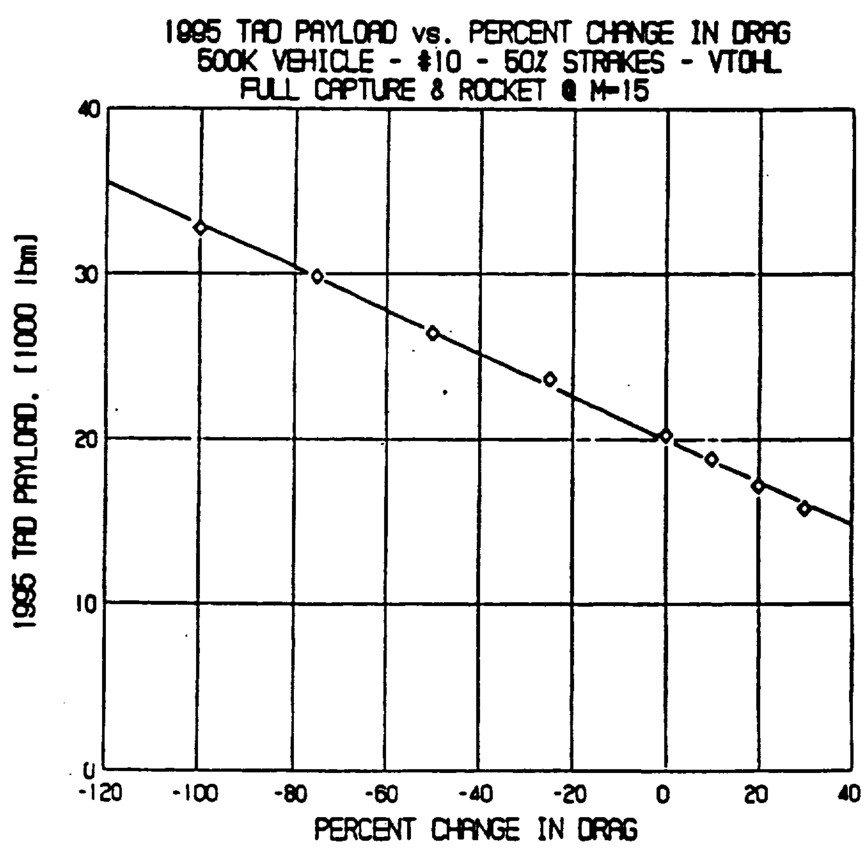
Angle of Attack vs. Mach Number for Varying Strake Sizes



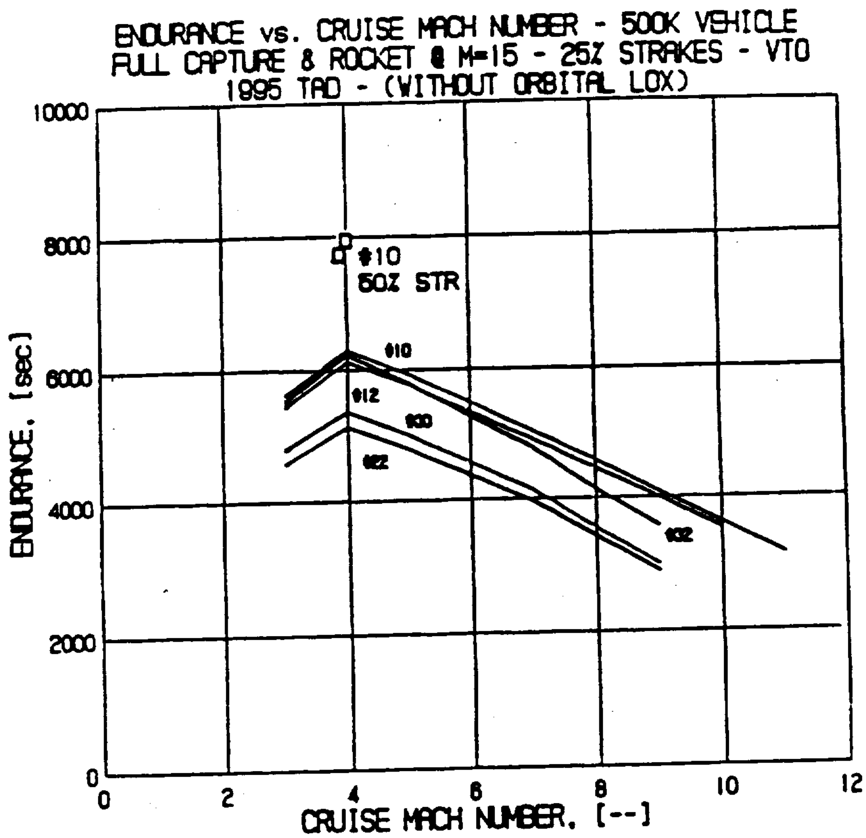
Payload vs. Strake Size for the Baseline Vehicle



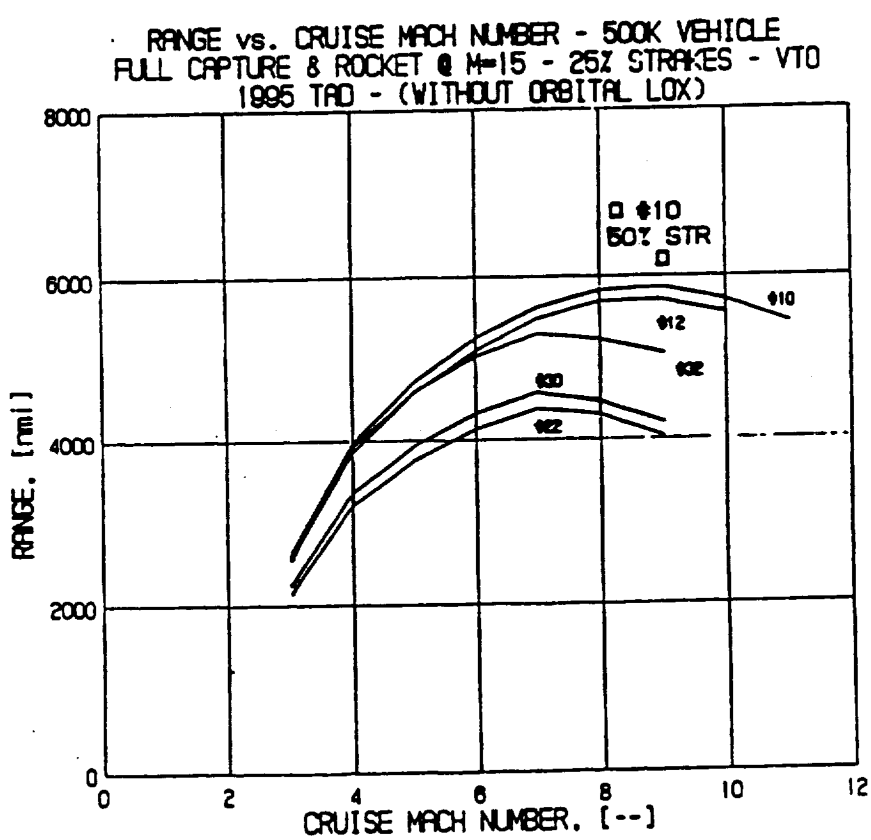
Effect of +/- 10% Isp Variation on Payload for the Baseline Vehicle



Payload vs. % Change in Drag Estimates for the Baseline Vehicle



Baseline Vehicle Endurance vs. Cruise Mach Number



Baseline Vehicle Range vs. Cruise Mach Number

CONCLUSIONS - EJECTOR SCRAMJET ENGINES AND AXISYMMETRIC CONSTRUCTION

1. Ejector Scramjet engines appear to provide adequate performance for space transportation missions.

2. The simplicity of the Ejector Scramjet engine, in comparison to other combined cycle propulsion systems should produce significant reliability advantages.

3. The axisymmetric configurations provides the lowest drag possible.

4. The axisymmetric configuration provides the highest structural efficiency, i.e., lowest inert weight.

5. The axisymmetric RBCC/SSTO vehicle design with 8 or more "modular" engines offers the lowest DDT&E and Production Phase costs when compared to non axisymmetric SSTO vehicles using fewer engines of larger thrust rating.

aar5

TASKS PROPOSED - FOR DISCUSSION

Task 1 - Thrust Vector Lift/Aerodynamic Lift Study

Task 2 - Upgrade Aerodynamics and Trajectory Analysis Findings

Task 3 - Forebody, Base Drag and Rocket Mode CFD Analysis

Task 4 - Vehicle, Propulsion and Ground Support Systems Design

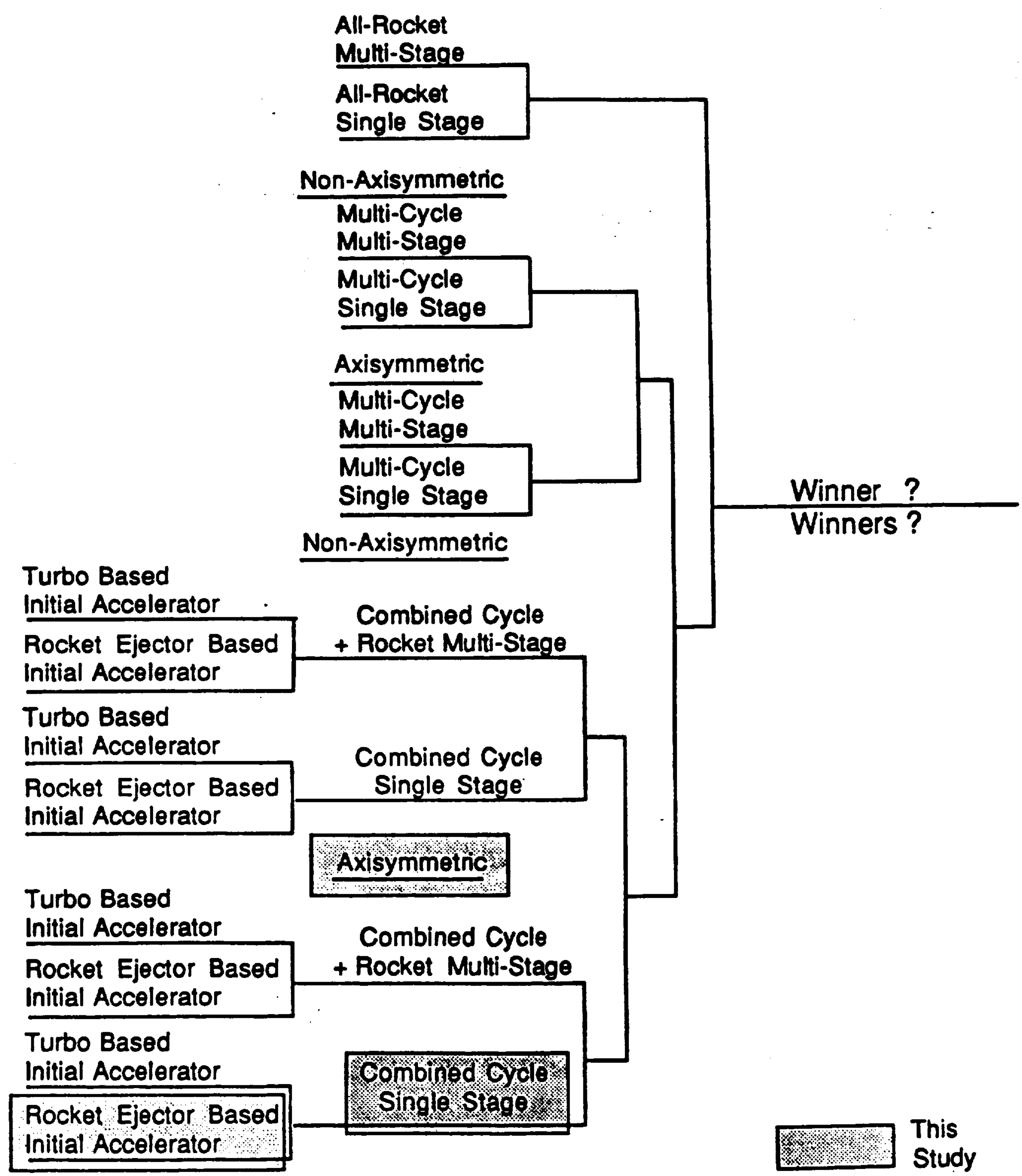
Task 5 - Vertical Landing

Task 6 - Upgrade Life Cycle Costs Analysis

Task 7 - Space Transportation System Characterization and Cost Analysis

aar4

Comparison to a common set of orbital transportation system requirements is required using a common set of analysis tools and methodologies.



S3911TWF/BQ

REFERENCES

CURRENT REFERENCES

Foster, R.W., Escher, W.J.D., and Robinson, J.W., Air Augmented Rocket Propulsion Concepts, Final Report, USAF Astronautics Laboratory Report AFAL-TR-88-004, April 1988

Foster, R.W., Escher, W.J.D., and Robinson, J.R., Studies of an Extensively Axisymmetric Rocket Based Combined Cycle (RBCC) Engine Powered SSTO Vehicle, AIAA Paper 89-2294, AIAA/ASME/SAE/ASEE 25th Joint Propulsion Conference, Monterey, CA, July 1989

Foster, R.W., Optimization of the Rocket Mode Trajectory in a Rocket Based Combined Cycle (RBCC) Engine Powered SSTO Vehicle, AIAA Paper 89-2295, AIAA/ASME/SAE/ASEE 25th Joint Propulsion Conference, Monterey, CA, July 1989

AFAL STUDY REFERENCES

Dixon, S.C., NASA R&T for Aerospace Plane Vehicles, Langley Research Center, NASA Technical Memorandum 86429, May 1985.

Escher, W.J.D., and Flornes, B. J., et al, A Study of Composite Propulsion Systems for Advanced Launch Vehicle Applications, Final Report on NASA Contract NAS7-377, The Marquardt Corporation, Van Nuys, CA, April 1967

Anon, Pre-proposal Contractor Briefing Package, ALS, System Contract #F04701-87-C-0101, USAF/AFSC, HQ Space Division, Los Angeles, CA, 5 May 1987

Simonson, A.J. and Schmeer, J.W., Static Thrust Augmentation of a Rocket Ejector System with a Heated Supersonic Primary Jet, Langley Research Center, NASA TND-1261, May 1962

Mossman, E.A., Rozycki, R.C., and Holle, G.F., A Summary of Research on a Nozzle-Ejector System, Martin Denver Research Report R-60-31, October 1960

Totten, J.K., Final Summary Technical Report on the Calendar Year 1963 Advanced Ramjet Technology Program, The Marquardt Company Final Technical Report under the Aeropropulsion Laboratory Contract AF 33(657)12146

Congelliere, J., Prevatte, N. and Lime, J., Advanced Ramjets Concepts, Vol II Ejector Scramjet Technology, The Marquardt Corporation, Report No. AFAPL-TR-67-118, May, 1968

Anon., Hypersonic Research Engine Project (Phase II), Final Oral Review Technical Presentation, Garrett AiResearch Report No. 75-1/338, NASA Contract NAS1-6666, 23 March 1975

Anon., Final Report - Hydrogen Turbofan Study, Garrett AiResearch Corporation for the Lockheed California Co. under NASA Langley Research Center Contract NAS-1-14614, NASA CR-145369, Vol. I, pp. 32-95, July 1978

Kumar, A., and Anderson, G. Y., Study of Hypersonic Inlet Flow Fields with a Three-Dimensional Navier-Stokes Code", AIAA Paper AIAA-86-1426, June 1986

Anon, YF-12 Experiments Symposium, NASA Conference Publication 2054, Dryden Research Center, September 1978

Puorto, J. W., SERJ Fan Integration Study, Final Report, The Marquardt Corporation, Report No. 25279, AD500754, February 1969

Hosack, G. A. and Stromsta, R. R., Performance of the Aerobell Extendible Nozzle, AIAA Journal of Spacecraft, Vol. 6, No. 12, pp 1416-1423, December 1969

Congelliere, J., et al, 1965 Advanced Ramjet Concepts Program Final Report Vol. III - Ejector SCRAMJET Analysis, The Marquardt Corporation AFAPL-TR-66-49, August 1966

Congelliere, J., Prevatte, N. and Lime, J., Advanced Ramjets Concepts, Vol II Ejector Scramjet Technology, The Marquardt Corporation, Report No. AFAPL-TR-67-118, May 1968

Flornes, B. J., and Davidson, G. R., Advanced Ramjet Concepts, Vol VIII, RamLACE/SCRAMLACE Propulsion Systems Analysis and Design, Technical Report AFAPL-TR-67-188, Vol. VII, The Marquardt Corporation, Van Nuys, CA, February 1968

Stull, F. D., Useful Scramjet Curves, a technical graph package obtained from the author, WPAPL, October 1984

Anon, Alternate Vehicle/Propulsion Study, Boeing Military Airplane Company and Rockwell International Space Transportation Systems Division presentation package, Jun 1985

Billig, F. S., and Beach, L. D., Hypersonic Propulsion, AIAA Sponsored Short Course Notes, Huntsville, AL, June 1985

Escher, W. J. D., and Doughty, D. L., Assessment of Cryogenic Hydrogen-Induced Air Liquefaction Technologies, Final Report to Science Applications International Corporation under Subcontract No. 15-860020-82, September 1986

Smith, L.R., Summary of Aerospace Program for 1963, The Marquardt. 1963 Annual Project Report under USAF Contract AF33(657)10796, Report No. APL-TDR-64-32, January 1964

McCarty, R.D., Hord, J. and Roder, H. M., Selected Properties of Hydrogen (Engineering Design Data), National Bureau of Standards Monograph, National Engineering Laboratory, Boulder, CO, USGPO 1981

Watson, K. A, DOF36 Program Users Guide, Air Force Wright Aeronautical Laboratories, Dayton, OH, April 1986

Watson, K. A., Analysis Development - 6-DOF Trajectory Simulation, Air Force Wright Aeronautical Laboratory, Dayton, OH, 1986

Freeman, Delma A., Advanced Space Transportation Studies Peer Review, NASA LaRC, 28 July 1987

Hoerner, Sighard F., Fluid Dynamic Drag, Hoerner Fluid Dynamics, Brick Town, N.J., 1975

Polhamus, Edward C., Predictions of Vortex-Lift Characteristics by a Leading Edge Suction Analogy, Journal of Aircraft, April 1971, Vol 8, No. 4, pp 193-199

Bertin, John J. and Smith, Michael L., Aerodynamics for Engineeers, Prentice Hall, Englewood Cliffs, N.J., 1979

Lindenbaum, B., V/STOL Concepts and Developed Aircraft, Final Report, AFWAL-TR-86-3071, Air Force Wright Aeronautical Laboratories, November 1986

Anon, Special Short Course in V/STOL Aircraft, AGARD Report AGARD-R-710, North Atlantic Treaty Organization Advisory Group for Aerospace Research and Development, May 1984

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	1992	Conference Publication

4. TITLE AND SUBTITLE

Rocket-Based Combined-Cycle (RBCC) Propulsion Technology Workshop
Tutorial Session

5. FUNDING NUMBERS

WU-590-21-11

6. AUTHOR(S)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E-6929

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CP-10090

11. SUPPLEMENTARY NOTES

Responsible person, William Escher, (202) 453-2858.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories 15, 16, and 20

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A Rocket-Based Combined-Cycle Propulsion Workshop is held at the University of Alabama in Huntsville under NASA Headquarters sponsorship. The goal of this workshop is to illuminate the Nation's space transportation and propulsion engineering community on the potential of hypersonic combined-cycle (airbreathing/rocket) propulsion systems for future space transportation applications. Appropriate background is provided at the workshop to participants and documented in this advanced conference proceedings. The Workshop's deliberative findings will be documented in subsequent proceedings.

14. SUBJECT TERMS

Rocket engine; Combined cycle; Propulsion; Transportation; Space

15. NUMBER OF PAGES 283

16. PRICE CODE A13

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	